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A Benefit Cost Model for Traffic Incident Management

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To the Graduate Council:

I am submitting herewith a thesis written by Sam Dallas Moss entitled "A Benefit Cost Model for Traffic Incident Management." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Civil Engineering.

Lee D. Han, Major Professor

We have read this thesis and recommend its acceptance:

Chris Cherry, Steve Richards

Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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A Benefit Cost Model for Traffic Incident Management

A Thesis Presented for the
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ABSTRACT

Every day, non-recurring incidents cause delay on major roadways and cost the public valuable time and, hence, money. Some public agencies have systems that help them to identify and mitigate the problems associated with incidents such as delay. These systems are referred to as Traffic Incident Management systems. Many different agencies have searched for a way to quantify the benefits that these programs provide. This thesis details how a model was developed to help these agencies easily quantify the benefits that can be derived from saving delay through efficient incident management. This model uses real traffic data collected by roadway traffic sensors to find the actual delay experienced by roadway users. It consists of 30 second aggregate data that measured the speed, occupancy, and flow at over 200 stations along the interstate system in Knoxville. It was collected by the Tennessee Department of Transportation in Knoxville, Tennessee and was used to help quantify the delay associated with incidents on the interstate. Another part of the dataset for the model included an incident log that recorded every incident that was reported or identified in Knoxville for the year 2009. Once the delays were quantified for each of the stations for every thirty seconds for the whole year, the benefits of a traffic incident management system could be calculated. The benefits were quantified by using the delay savings due to the incident management program, and thus, how much money was saved for each incident. The benefit in delay saved for the city of Knoxville was found to be $12.1 million dollars. The costs for the Knoxville system were $1.43 million dollars, thus giving a benefit cost ratio of approximately 8.5:1. The model developed to determine this benefit cost ratio can be applied to other places and reused with only minor adjustments that do not require extensive data collection. This is advantageous because it requires less time and effort to calculate the benefits of any particular incident management system.

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CHAPTER I
INTRODUCTION

The purpose of Traffic Incident Management (TIM) is to quickly and efficiently detect, respond to, and clear traffic incidents so that traffic flow may be restored as safely and efficiently as possible (FHWA 2011). In order to evaluate the effectiveness of a TIM program, one must quantify the benefits in a way that objectively and accurately reflect the program's goals. There are several ways to quantify the benefits including improvements in safety, mobility, capacity, customer satisfaction, and environmental impacts. One of the safety benefits derived from a TIM program is a reduction in the number of secondary crashes. In terms of mobility, a TIM program helps in reducing the travel time delay of individual vehicles. Capacity can be helped by a TIM program through optimizing the use of existing facilities. Customer satisfaction is a measure of the effectiveness of the program from the user's perspective. The environmental benefits can be measured in terms of reduction in emissions and fuel consumption (Han 2010).

Tennessee Department of Transportation's (TDOT's) "SmartWay" was implemented in 1999 and consisted of freeway service patrols in Knoxville and Nashville, Tennessee which patrol the freeways and provide assistance to motorists and aid in accident clearance. Since 1999 the system has been expanded and now includes 700 Roadway Traffic Sensors (RTS), 250 traffic cameras, 78 Dynamic Message signs, three transportation management centers, and freeway service patrols for Knoxville, Nashville, Memphis, and Chattanooga (TDOT 2011).

Customer satisfaction has been reviewed previously by TDOT but the benefits of delay savings were not quantified. An examination of previous benefit costs analyses for other TIM programs revealed that there was a need for a model that could be applied to all locations in the country and could be used on a macroscopic or a microscopic scale.

The purpose of this thesis is to develop a model that can derive the benefits of a TIM program and be adjusted to any region in the country. This model is capable of calculating the delay savings that come from an effective TIM program. This model is adjustable for use in planning purposes and for review of current systems. It can also be used in either microscopic or macroscopic applications. The model should be used in conjunction with an incident log when the demand, or average annual daily traffic (AADT), and network constraints, such as capacity, are known.

This model was developed using an incident log provided by TDOT, the capacity of the interstate network in Knoxville, Tennessee, and 30 second aggregate data that included volume, occupancy, and speed information for over

200 locations in Knoxville. These data were chosen because of their high accuracy and reliability as compared to other locations throughout the state. The incident log was provided by the Knoxville Transportation Management Center and was used to identify when an incident occurred. It was the only incident log available when the study began. This model evaluates the benefits in terms of money saved from the productivity improvements due to delay reduction. This method of evaluation was chosen because it is the easiest method to directly quantify, and can be measured using the existing infrastructure and available data in the program studied.

Knoxville, the site of the case study, is at the intersection of two major interstates; I-40 which runs east to west and I-75 which runs north to south. The two roadways are combined for a significant portion to the west of Knoxville and there is a bypass around the north of the city of Knoxville called I-640. Additionally, I-640 and I-75 are combined for a portion to the northwest of downtown until I-75 splits off and runs north away from downtown. A roadway, called I-275, connects I-75 to I-40 from downtown directly to the place where I-75 splits off from I-640 and heads north. Furthermore, an extension of I-40 called I-140 connects the west side of Knoxville to the city of Alcoa to the south of Knoxville. A map of the Interstate Highways around Knoxville can be seen in Figure 1.

Figure 1: A Map of The Interstate Highways around Knoxville, Tennessee

CHAPTER II
LITERATURE REVIEW

Many of the public agencies that have TIM programs have conducted benefit cost studies of their programs. Some of these studies relied on modeling software to assess the benefits of the programs. Other studies used analytical approaches such as a queuing model or kinematic wave theory to analyze delay caused by incidents. These studies typically focused on incident delay savings but could also include reduction in fuel consumption, lower emissions, avoided secondary crashes, and other safety benefits.

According to Short Elliot Hendrickson Inc., the biggest assumption that most benefit cost studies make is the effect that a TIM program will have on the duration of the incident. Most studies assumed that the TIM program reduced the duration of a type of incident by a certain time but a few others studied the before and after effects of a TIM program and calculated the actual time saved. The average of the stated incident reduction times for the studies reviewed, either assumed or calculated, is 17.8 minutes. A list of all the times used by other benefit cost studies that were reviewed can be found in Table 1. A summary of the average incident reduction times used by other studies for each of the incident types that the Tennessee Department of Transportation (TDOT) uses can be found in Table 2. TDOT states that the law enforcement officers in the state have reported a reduction in accident investigation time of 30% (Baird 2003) while a report for Washington State DOT reported an average of about 8 minutes saved for total clearance time (Sun 2010). Accident response times with TIM were reported to be about 8 minutes on average in Missouri (Nee 2001) and about 44-77% faster in Washington state (Sun 2010).

Previous benefit cost studies can be grouped into four categories:

- Ones that used data collected from the roadway to calculate delay.
- Ones that used roadway data to calculate delay and then compared them to simulation models that also calculated delay.
- Ones that only used a simulation model to calculate delay.
- Ones that used an existing evaluation model to calculate a benefit cost ratio.

Some of the program benefit cost studies that used data collected from roadway sensors are the Georgia Navigator study (Guin 2007) and the St. Louis, Missouri study (Sun 2010). One of the benefits of a benefit cost study that used roadway data to calculate delay is that there was no estimation of the delay; instead, it was calculated directly. A drawback to having used only collected data to calculate delay for a benefit cost study is that there was no comparison of the

Table 1: Incident reduction times in minutes used by previous benefit cost studies.

Region	Incident Type	Incident Duration Reduction (minutes)
Boston[1]	minor incident.	15
	disabled	25
	moved to shoulder	25
	debris	30
	accident in lane	20
Chicago[2]	accidents on the shoulder	20
	accidents in 1 lane	35
	accidents in 2 or more lanes	40
Denver[3]	lane blockers	10.5
	non-blockers	8.6
Gary, IN[4]	crash/ in lane assist	10
	others	15
Houston[5]	minor incident average	16.6
San Francisco[6]	breakdowns	16.5
	crashes	12.6
Minnesota[7]	stall less than 30	8
	stall thirty to an hour	5
	stall over an hour	0
Virginia[8]	accident	43.5
	breakdown	25.0
	debris	5

[1] Stamatiadis 1997
[2] Fenno 1997
[3] Cuciti 1995
[4] Latoski 1999
[5] Hawkins 1993
[6] Skabardonis 1995
[7] Minnesota DOT 2000
[8] Dougald 2007

Table 1 (continued)

Region	Incident Type	Incident Duration Reduction (minutes)
Washington[9]	disabled	4.3
Missouri[10]	all	15
Georgia Navigator[11]	incident	45.9
Florida[12]	all	20
New Jersey[13]	all	7-20

[9] Nee 2001
[10] Sun 2010
[11] Guin 2007
[12] Hagen 2005
[13] Ozbay 2005

Table 2: Average incident reduction times in minutes from other benefit cost studies for the eight types of incidents as identified by TDOT.

	Location					
Incident Type	shoulder	1 lane	2 lanes	3 lanes	4+ lanes	median
accident	20.3	20.5	21.0	21.0	21.0	20.3
fire	17.6	17.6	17.6	17.6	17.6	17.6
disabled	15.6	15.6	15.6	15.6	15.6	15.6
abandoned	17.6	17.6	17.6	17.6	17.6	17.6
debris	17.6	17.6	17.6	17.6	17.6	17.6
pedestrian	17.6	17.6	17.6	17.6	17.6	17.6
other	17.1	17.1	17.1	17.1	17.1	17.1

delay values to anything. This could be misleading if an error occurred in the calculation of delay or benefits.

The “FIRST” program benefit cost study used roadway data to calculate delay savings due to the program and compared the results to delay savings generated by a computer model (Hendrickson 2004). Washington State’s TIM program benefit cost study also used roadway data to calculate delay savings and compared the results to model calculations (Wang 2008). Because these studies used data collected from traffic and compared the delay savings to a computer model there is good redundancy in the studies. One of the drawbacks of these studies is that they could contain inaccurate estimates of the delay because of the limited number of actual cases used in the delay calculations.

One of the benefit cost studies that used only simulation data is the evaluation of the “CHART” program in Maryland (Chang 2002). This study used CORSIM to model the benefits from incident delay. This study also compared two different years of data to analyze any changes in the benefits of the “CHART” program. Another benefit cost study that used only model simulation data was the one conducted on Arizona’s “REACT” program (Battelle 2002). “REACT’s” objective is to provide management for emergencies on arterial roadways (Battelle 2002). This study used a simulation to assess the benefits of the program but, due to the nature of the program, only two simulations were used to estimate the benefits. One of the benefits to using only a simulation model is that there is no need to collect large amounts of data. Only a few parameters are needed to use a simulation model such as capacity and demand. One of the drawbacks to this is that there is no data to compare the simulation results to. This results in conclusions that are hard to verify.

The Florida Road Ranger program used a model know as Freeway Service Patrol Beat Evaluation (FSPE) in its benefit cost study (Hagen 2005).

This model was developed to analyze the benefits of a freeway service patrol program. This is an effective model; however, there is no adaptability to any specific area. Because the study was located throughout the entire state of Florida, the same model was used for parts that can be very different in accessibility, geometry, or other characteristics. In addition, there are a limited number of types of incidents that can be distinguished using FSPE. The benefit cost study in Hampton Roads, Virginia used FSPE to evaluate their freeway service patrol program (Dougald 2007). The main distinctions of this program were its limited area and a before and after study which provided a detailed assessment of the actual clearance time improvements of the TIM program. One of the drawbacks of these studies is that there were no data for overall delay to use in comparison with the FSPE output.

The average benefit cost ratio for previous studies was about 13.1:1 ranging from a low of 2.3:1 to a high of 41.5:1. A list of some of the benefit cost studies reviewed along with their respective benefit cost ratios can be found in Table 3.

This research differs from the previous studies in that its purpose is to develop a model that estimates delay saved by a TIM program using actual data, and has the ability to be adapted to other locations. This model is also different because the data that were used to calculate delay were from a random sample taken from many days of delay data that were calculated for an entire year. The samples of data were later compared to the actual data from the entire year to see if the estimates for total delay values were similar to the measured total delay values. One benefit of using this model is that it will reduce the amount of data needed to perform a benefit cost analysis on an existing TIM program by allowing minor adjustments for changes in capacity and demand in different locations. Finally, this model can be easily adjusted to reflect different types of incidents beyond breakdowns, accidents, and debris; it can calculate delay savings for the eight different categories that TDOT uses to identify different incidents.

Table 3: Benefit cost ratios of previous reviews.

Region	B/C Ratio
Boston[14]	19:1
Chicago[15]	17:1
Denver[16]	10-16:1
Gary, IN[17]	13:1
Houston[18]	7-36:1
Houston Special Program[19]	19.4:1
Los Angeles[20]	3.8-5.5:1
San Francisco[21]	3.4:1
Minnesota[22]	4.4:1
Virginia[23]	4.6:1
Missouri[24]	38:1
Georgia[25]	4.4:1
Florida Overall[26]	25:1
Florida[27]	2.3-41.5:1
North Carolina[28]	3.5-4.3:1
South Carolina[29]	8:1
Arizona[30]	6.5-8.5:1

[14] Stamatiadis 1997
[15] Fenno 1997
[16] Cuciti 1995
[17] Latoski 1999
[18] Seigfried 1991
[19] Hawkins 1993
[20] Skabardonis 1998
[21] Skabardonis 1995
[22] Minnesota DOT 2000
[23] Dougald 2007
[24] Sun 2010
[25] Guin 2007
[26] Clark 2005
[27] Clark 2005
[28] Khattak 2005
[29] Chowdhury 2007
[30] Battelle 2002

CHAPTER III
ANALYSIS METHODS

The purpose of developing this model is to be able to quantify the benefits of a TIM system. A case study in Knoxville, Tennessee was used to help quantify the delay savings associated with a TIM system. In order to find the delay savings the number of incidents needed to be known, the delay savings for each of those incidents needed to be calculated, and the savings needed to be quantified in a way that is comparable to the cost of the system.

Incident Log

An incident is defined as any non-recurring event that causes a reduction in the capacity of a roadway or an abnormal increase in demand (Owens 2010). Each incident in Knoxville, Tennessee that is reported by the Traffic Management Center (TMC), roadway service patrols (HELP trucks), the local authorities, or by any citizen is recorded in an incident log that is kept for records with TDOT. The incident log contains information about the time the incident was identified, the type of incident that occurred, when a HELP truck was dispatched, the location of the incident, what service was provided to aid motorists, the date it occurred, and when the incident was resolved. For the year 2009, 14,996 incidents were recorded in the incident log for the interstates within the boundaries of the Knoxville SmartWay system alone.

There were too many incidents for the year 2009 to calculate the delay associated with each one, therefore, every incident in the incident log was classified based on four parameters:

- Incident cause, the incident causes as identified by TDOT are: Accidents, Vehicle Fires, Disabled Vehicles, Abandoned Vehicles, Roadway Debris, Pedestrians, Other, and No Note Incidents.
- The time of day, which was meant to be representative of the demands experienced at different times of the day, was divided into four time periods: Morning Peak from 6 AM until 10AM, Mid-Day from 10 AM until 3 PM, Afternoon Peak from 3 PM until 7 PM, and Off Peak from 7 PM until 12 AM and from 12 AM until 6 AM.
- The duration, which was divided into four lengths: Less Than One Hour, One to Three Hours, Three to Five Hours, and Greater than Five Hours.
- The location, which accounts for the different effects an incident’s lane location would have on the delay, was divided into six locations: Shoulder, One Lane, Two Lanes, Three Lanes, Four or More Lanes, and Median.

Each incident was classified into one group for each of the four parameters allowing the delay of similar incidents to be estimated based on common criteria; therefore, a representative sample of the data can be used to estimate the delay for similar incidents. Once the incidents were classified, they were organized into different matrices that represent groups of incidents with similar delays. Each matrix consists of a count of all the incidents for each cause and each location and there is one matrix for each combination of time of day and duration categories. There are 768 individual cells, each containing the number of incidents that occurred for each classification, comprising sixteen similar matrices corresponding to each time and duration category. A sample of one of the organizational matrices is presented in Table 4 while all of the matrices can be found in Appendix 1.

Data

In order to find the delay experienced by roadway users, speed, volume, and occupancy data collected by 213 radar and video roadway traffic sensors were gathered from TDOT. The data were for the year 2009 and covered most of the freeways through and around the city of Knoxville.

The roadway traffic sensors were powered by solar panels; therefore, continuous data collection was not always possible. On days when there was not much sunlight there could be missing data. There were also missing values occurring infrequently throughout some days due to random errors in the data collection devices. In order to correct the missing data points where possible, an imputation method which followed an algorithm that derives the likely values of speed, volume, and occupancy separately during a given time window was used. The time window was defined by the number of data points before and after the

Table 4: The number of incidents for each type of cause and location occurring during the “Morning Peak” time period and lasting for less than one hour.

CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median	TOTAL
Accident	193	17	7			17	234
Vehicle Fire	4	1				0	5
Disabled	1486	181	51	7		97	1822
Abandoned	511	172	29	9		58	779
Debris	266	27	6	1		14	314
Pedestrian	2					1	3
Other	170	13	6	2		19	210
No Note	11	2				0	13
TOTAL	2643	413	99	19	0	206	3380

missing data and within a maximum of eight minutes, and the data points were given more weight if they were closer in time to the missing values.

Delay Calculation

The delay was calculated by applying the fundamental traffic stream relationship, where flow is equal to density multiplied by velocity, to the speed, volume, and occupancy data for every thirty second interval of every day. A total travel time for each segment between stations can be calculated using equation 3.1:

$$\int k_i L_i \, dt = \int \frac{L_i}{v_i} q_i \, dt \quad (3.1)$$

Over a duration of m for n segments, we have the total travel time, T, as:

$$\sum_j \sum_i N_i \frac{5280 L_{ij}}{L_e} \phi_{ij} = \sum_j \sum_i \frac{L_{ij}}{V_{ij}} C_{ij} \quad (3.2)$$

L_e is dependent on the mix of traffic and can change over i and j. But if the mix of traffic were known and relatively stable, a fixed value, e.g. 26.4 feet, may be used. This transforms equation 3.2 into:

$$200 \sum_j \sum_i N_i L_{ij} \phi_{ij} \; ; \; \sum_j \sum_i \frac{L_{ij}}{V_{ij}} C_{ij} \quad (3.3)$$

During normal, non-congested conditions, either side of the equation should work. If v_{ij} were somehow unavailable, one can assume an average operational speed of V_b for all i and j:

$$T_{normal} = \sum_j \sum_i \frac{L_{ij}}{V_b} C_{ij} \quad (3.4)$$

If there are periods of congestion where traffic count $C_{ij} = 0$, an alternative way of calculating the total travel time over a duration of m for n segments is:

$$T_{congesgted} = 200\sum_{j}\sum_{i} N_i L_{ij} \phi_{ij} \quad (3.5)$$

Using these equations, the total delay over the duration of m for n segments can be calculated as:

$$Delay = 200\sum_{j}\sum_{i} N_i L_{ij} \phi_{ij} - \sum_{j}\sum_{i} \frac{L_{ij}}{V_b} C_{ij} \quad (3.6)$$

These equations illustrate that the delay is equal to the travel time under congested conditions minus the travel time under normal conditions where the variables are given in Table 5.

An algorithm was used to apply these equations to the average speed, flow, and occupancy data and calculate the delay. The algorithm consisted of three conditions. The first condition was that if the traffic speed was greater than or equal to the speed limit, then the delay would be equal to zero. The speed limit was chosen as the baseline speed for delay because under normal, non-incident conditions, the traffic flowed at a higher speed than the speed limit. If a higher value was chosen, it could imply that TDOT expects the public to travel at a speed greater than the posted speed limit and anything below that higher speed would be considered delayed traffic. The second condition stated if the

Table 5. Variables used in the previous equations to obtain delay.

Variable	Meaning
C_i	Traffic count at station i for dt, in number of vehicles
dt	Size of time slice, e.g. 30 seconds
i	A roadway segment centered around sensor station i
j	A time slice of the size of dt, e.g. 30 seconds
k_i	Density in segment i, in vehicles/mile/lane
L_e	Length of an average vehicle, in feet, about 26.4 feet
L_i	Length of segment i, in miles
m	Number of (30-second) time slices in the analysis
n	Number of roadway segments in the analysis
N_i	Number of lanes in roadway segment i
q_i	Flow rate at station i, in vehicles/hour/lane
v_i	Average speed at sensor i
V_b	Average normal speed for the duration of dt at sensor i, in miles/hour
V_i	Average speed for the duration of dt at sensor i, in miles/hour
Φ[phi]$_i$	Occupancy at station i, in percent

traffic speed was less than the speed limit and greater than zero, then the delay would be equal to the actual travel time for the segment minus the travel time at the speed limit as per equation 3.6. The third condition was that if the traffic speed was equal to zero, then the traffic count and the occupancy must be checked to see if they were also equal to zero. If so, then the delay would be zero. However, if this was not true, then traffic is present but not moving and the delay can be calculated as per equation 3.5. Applying this model to all the data gives the delay for every thirty second interval at every station for the whole year.

The delay was determined by a fixed speed that was typically found to be lower than the average free flow speed; therefore, the total amount of delay calculated was probably lower than the actual delay experienced by the roadway users. This means that the delays might be underestimated or might not be counted by the algorithm.

Incident Comparison

After the delay is calculated for every thirty second interval and every station for every day, the delay can be compared to the incident log to find the total delay for each type of incident. In order to assure the accuracy of the start time in the incident log, a preliminary check of each type of incident was done to find the average duration and length in stations for each type of incident. Only the days where 90% of the data were available were used in order to find the duration and length, in stations, with the best accuracy. Once these higher reliability days were found, a random sample of incidents was drawn from the incident log on these days. Each incident was compared to the station maps, shown in figures 2 and 3, to match the location of the incidents to the correct stations for analysis. Using the speed, flow, and occupancy data the actual duration and number of stations that were affected by each incident was determined for each incident in the sample. For each incident cause, the average values calculated are shown in Table 6.

Table 6: Initial values for a random screening of incidents with greater than 90% of the data available.

	Accident	Fire	Disabled	Abandoned	Debris	Pedestrian	Other
Duration	31.875	78.3	10	50	35	30	13.33
Number of Stations	2	5.75	1	1	1	1	1

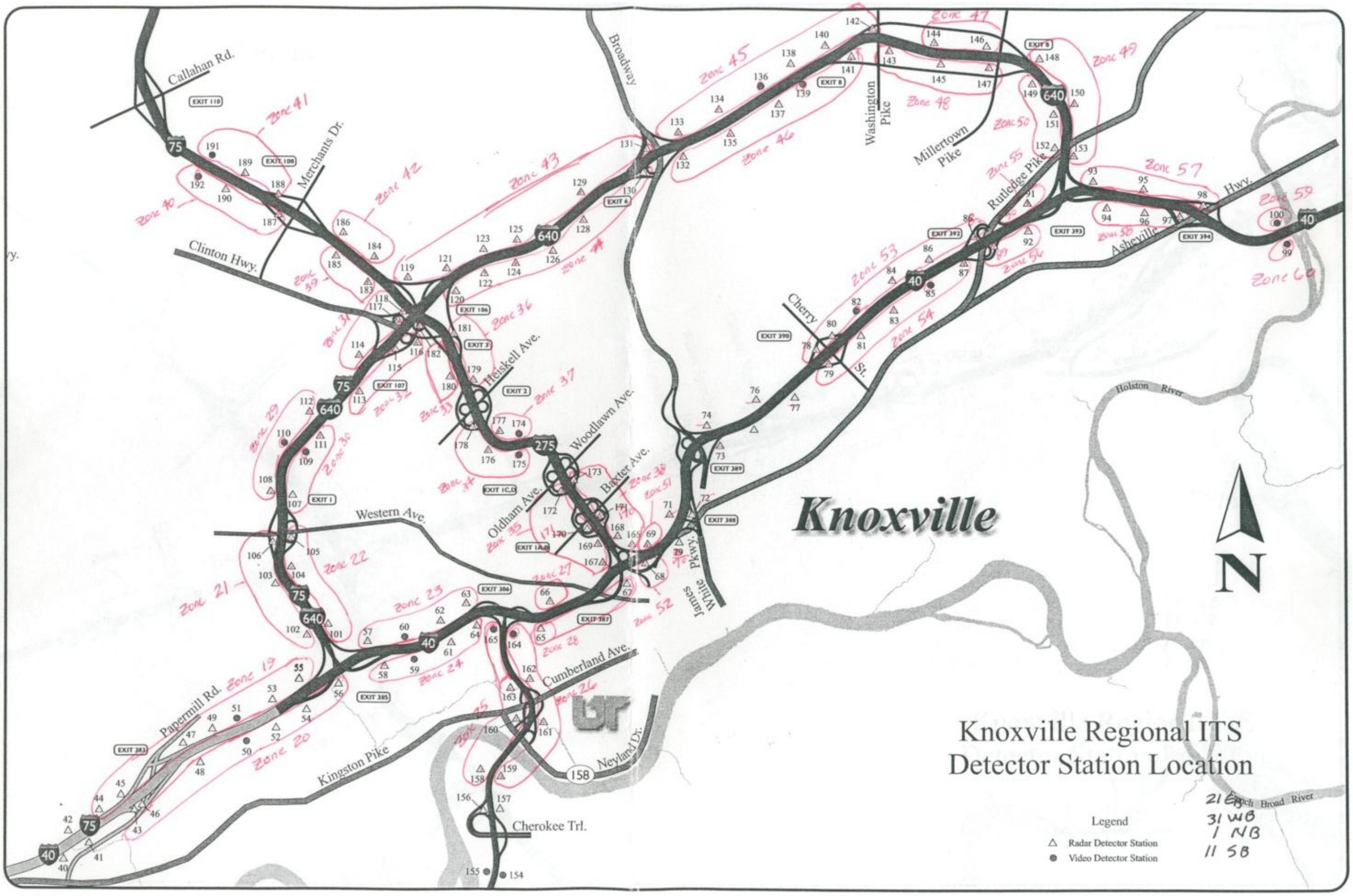

Figure 2: A map of the RTS stations for downtown Knoxville, Tennessee courtesy of TDOT.

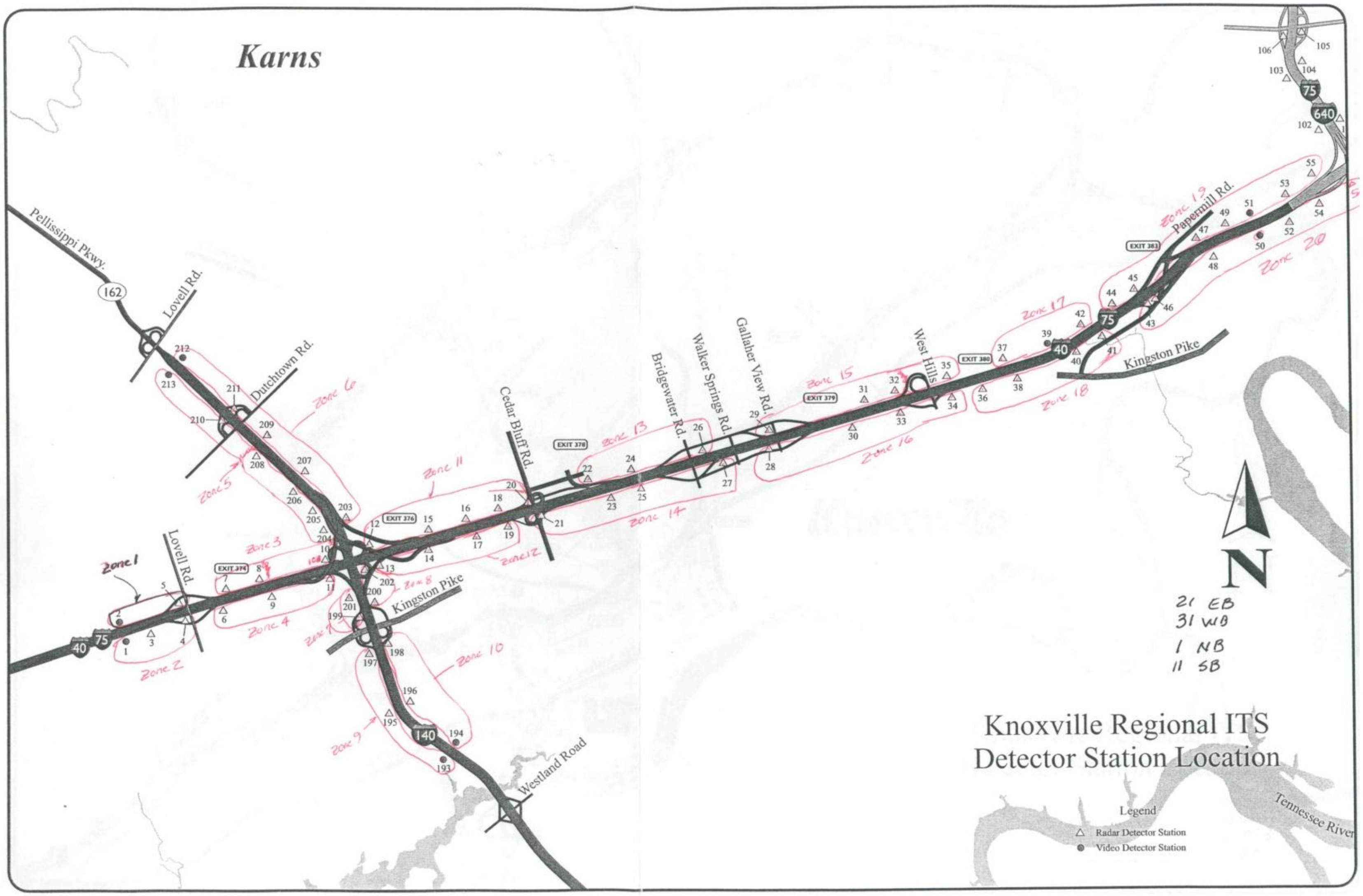

Figure 3: A map of the RTS stations to the west of downtown Knoxville, Tennessee courtesy of TDOT.

There were no incidents in the log that fell under the category of “No Note” and they were therefore excluded from the initial analysis. These incidents were assumed to have been added to the “Other” category and the categories were combined.

After the initial average values of the duration and stations for each of the incident types were found, another random sample was taken from the incident log. The 90% data were not used again because too few of the days had 90% or greater reliability and would not have produced a good sample. The new random sample was taken from the days that contained 80% of the data available and consisted of fifty days for each type of incident where possible. In the cases where it was not possible to have a sample of fifty incidents due to a small number of incidents of that cause, all of the days available were sampled.

The new sample of incidents from the incident log was compared to the maps in figures 2 and 3 to determine and record the closest upstream station to the incident. Downstream stations were not considered because the initial analysis showed that their speed was not affected by the incidents. This was possibly because after passing the incidents, traffic resumed normal operating speed. After the location was determined for each incident in the sample the delay was then calculated using a filter that found the delay for the average number of upstream stations for each category and for a prescribed period of time before and after the incident discovery time was recorded. The time buffer before and after an incident was based on findings from the initial analysis. A list of the filter parameters for each incident type is in table 7.

Once an initial recording of the delays were found for the sample, a second check of the data was performed. The second check entailed filtering out the incidents in the sample that had over 50,000 seconds of delay. This value was chosen because it was found to be roughly equal to a thirty minute incident blocking one lane. Incidents with less delay would likely be hard to notice when observing speed and occupancy changes and were therefore not inspected in depth. Once these days were identified, a thorough investigation of these incidents was done by hand to determine the exact extent of the incident in time and number of stations in case the delays were not properly recorded using the

Table 7: Filter values used to determine the delay for each incident type at the appropriate stations.

Filter Parameter	Accident	Fire	Disabled, Abandoned, Pedestrian, and Other	Debris
Stations Used	3	5	1	1
Time Before (min.)	30	90	30	45
Time After (min.)	30	60	30	30

filter. This investigation included checking all of the surrounding stations to determine the geographic extent of an incident to ensure that all of the stations that could have recorded delay caused by the incident were used and by checking the beginning and ending time of the incident to ensure that the entire incident was counted by the delay comparison.

Once the delay values were found for each of the incidents, the recurring delay needed to be subtracted out. This was accomplished by recording the delay on another day in the same place and time using the same filter as the day of the incident. Once the delay was known for both days the delay from the non-incident day was subtracted from the delay measured on the day of the incident.

No extensive analysis was performed to find the true baseline delay for each particular area because of the lack of first-hand knowledge of each location. An incident could be occurring at any time and might not be recorded by the incident log, it would then be erroneously incorporated into the baseline data.

Delay Savings

The total delay caused by an incident can be directly calculated by applying the equations derived from the fundamental traffic stream relationship. However, this will not give the delay that was saved by an incident management program. In order to find the delay benefits of an incident management program, the delay caused by an incident without the incident management system must be known. Due to the absence of historical data, no record of delay before the SmartWay system was in place exists. Because of this, the queuing diagram was used to estimate what the delay would have been in the absence of the incident management program. The basic queuing diagram, shown in Figure 4, was modified to represent the total delay if an incident's duration were extended. The modified queuing diagram, as seen in Figure 5, illustrates a comparison between the actual delay and the delay that would occur without an incident management system. In order to calculate the delay benefits, equations were derived from the modified queuing diagram. These equations whose variables are defined in Table 8 are:

$$\lambda[\text{lambda}](T_H + \Delta[\text{delta}]t_1) = S_I * T_H + S * \Delta[\text{delta}]t_1 \quad (3.7)$$

$$A_H = \frac{1}{2}x(T_H + \Delta[\text{delta}]t_1) \quad (3.8)$$

$$x = (\lambda[\text{lambda}] - S_I)T_H \quad (3.9)$$

$$\lambda[\text{lambda}](T_H + \Delta[\text{delta}]t_2 + \Delta[\text{delta}]T) = S_I(T_H + \Delta[\text{delta}]T) + S * \Delta[\text{delta}]t_2 \quad (3.10)$$

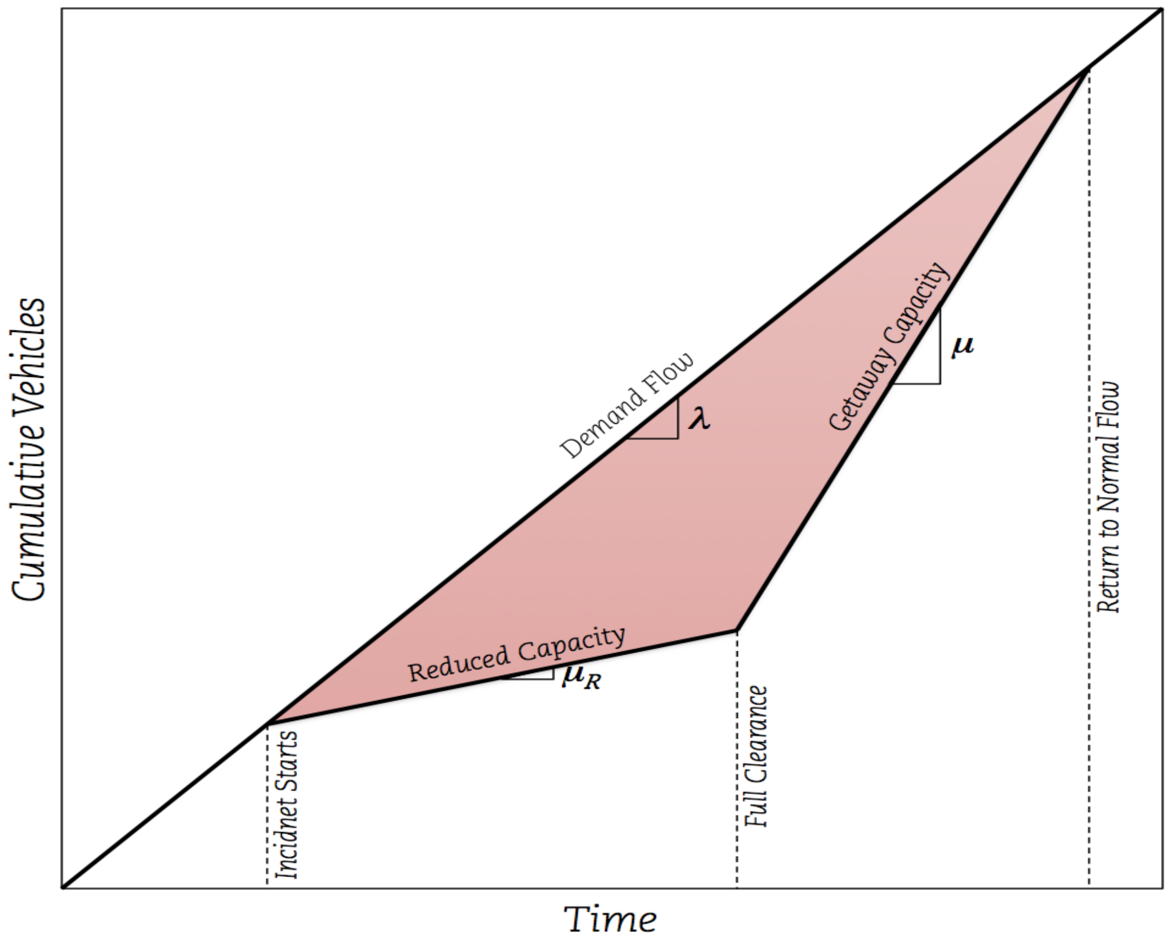

Figure 4: The standard queuing diagram.

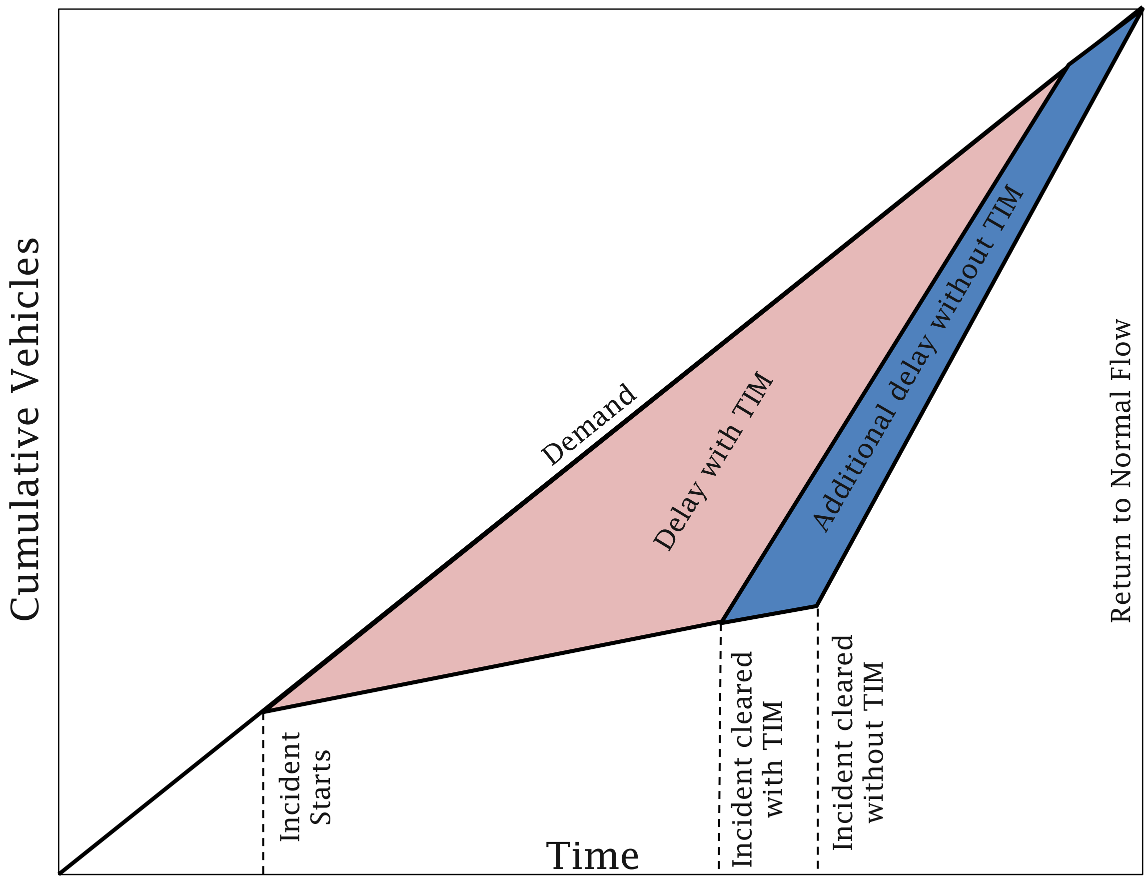

Figure 5: Queuing diagram showing the effect of extended duration on total delay.

Table 8: Variables for the equations derived from the queuing diagram.

Variable	Meaning
λ[lambda]	Demand
T_H	Incident Duration
Δ[delta]t_1	Time until normal conditions are restored after incident with incident management
S_I	New capacity caused by the incident
A_H	Delay caused by the incident with incident management
x	Maximum number of vehicles delayed with incident management
Δ[delta]T	Time savings from incident management
Δ[delta]t_2	Time until normal conditions restored after incident without incident management
y	Maximum number of vehicles delayed without incident management
A	Delay of the incident without incident management

$$y = (\lambda[\text{lambda}] - S_I)(T_H + \Delta[\text{delta}]T) \quad (3.11)$$

$$A = \frac{1}{2}y(T_H + \Delta[\text{delta}]t_2 + \Delta[\text{delta}]T) \quad (3.12)$$

$$\frac{A - A_H}{A_H} \quad (3.13)$$

Equation 3.13 represents the delay savings ratio which is the delay saved divided by the delay calculated. This delay savings ratio can be multiplied by the delay calculated to get the theoretical delay savings. This was done for each cell in the matrices. For cells that had no samples available to obtain the delay needed, the queuing diagram was used to help determine the theoretical value of delay that would occur. An assumption had to be made about the time saved due to the incident management program. The assumption was that the incidents lasted fifteen fewer minutes than before the program was enacted. This assumption was for all incident types and all durations at any time of day and every location.

Capacity and Demand

The standard capacity for freeways in Knoxville is estimated to be around 1500 vehicles per hour per lane including trucks in rolling terrain. This value was checked by comparing the peak vehicle count data over a fifteen minute period and was found to be roughly equivalent. In the first half of 2009 I-40 was under construction from mile marker 388 to mile marker 389 in Knoxville. This construction project was called “SmartFix 40” and caused the interstate to be completely closed to through traffic and an alternate route had to be used for most traffic. This caused a need to add an additional lane to I-640 around Knoxville in order to handle the increased flow on this roadway. Because of the expansion to I-640, a majority of the city of Knoxville had four or more lanes on the interstate in each direction. The exceptions were I-275 and I-75. During the portion of the year after Smart Fix 40 was completed, most of the interstate in Knoxville remained 4 or more lanes. Because of this, the Knoxville analysis assumes that most of the incidents occurred on a section of the interstate that contained four or more lanes in each direction. This leads to the determination that a majority of the interstate roadway in Knoxville in 2009 had a capacity of around 6000 vehicles per hour per direction.

Capacity is constant for most of the roadway in Knoxville except in certain areas where weaving sections reduce the effective capacity and other natural bottlenecks affect traffic flow. When an incident occurs it causes a drop in the capacity of the roadway. Other studies have shown that the location of the incident along with the type of incident and how many lanes are affected all have an effect on the actual capacity of the roadway (Chou 2009). The actual capacity after an incident occurs is hard to quantify but a range of values, found in table 9, were used to calibrate the model in order to fit the measured delays to the theoretical delays as determined from using the queuing diagram.

Demand is the actual number of users who use the roadway. Knoxville has a large variance in demand from one roadway to another as shown in figures 6 and 7 while graphs of the numbers of vehicles in various locations around Knoxville can be found in Appendix 5. For this reason it was necessary to use average values for the region when calculating the delay savings. It was also important to know the correct demand amounts for interpolating the amount of delay for incidents that were not included in the sample. Some of the peak values were close to 7200 vehicles per hour per direction on the five lane portions of the interstate while the three lane portions peaked at around 3600 vehicles per hour per direction. The demands used to match the measured delays from the sample to the queuing diagram's theoretical delays were: 4500-5000 vehicles per hour for the AM and PM peaks, 4000-4500 vehicles per hour

Table 9: Capacity reduction factors used in the Knoxville, Tennessee case study for each location type

Location	Proportion of Capacity
Shoulder	.85-.99
One Lane	.58-.66
Two Lanes	.25-.28
Three Lanes	.13-.15
Four or More Lanes	0.0
Median	.74-.80

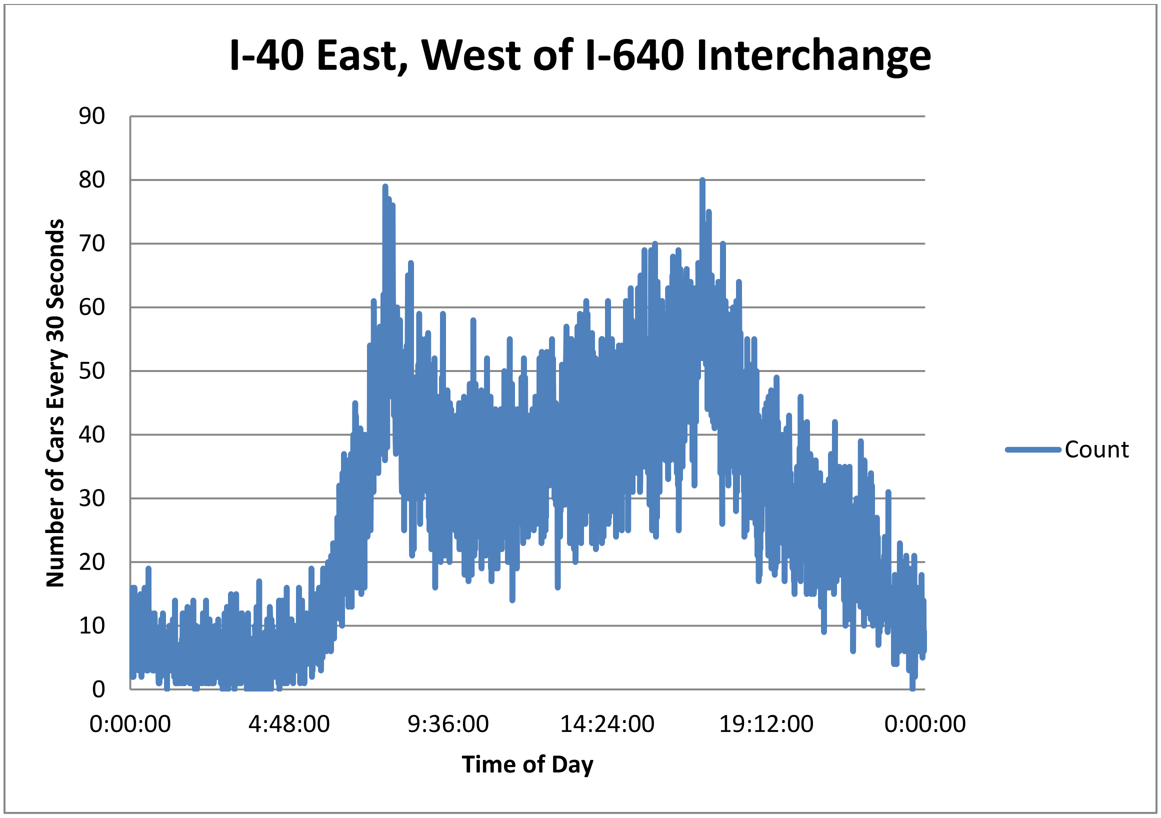

Figure 6: 30 second aggregate counts of traffic volumes on eastbound I-40 west of the I-640 interchange

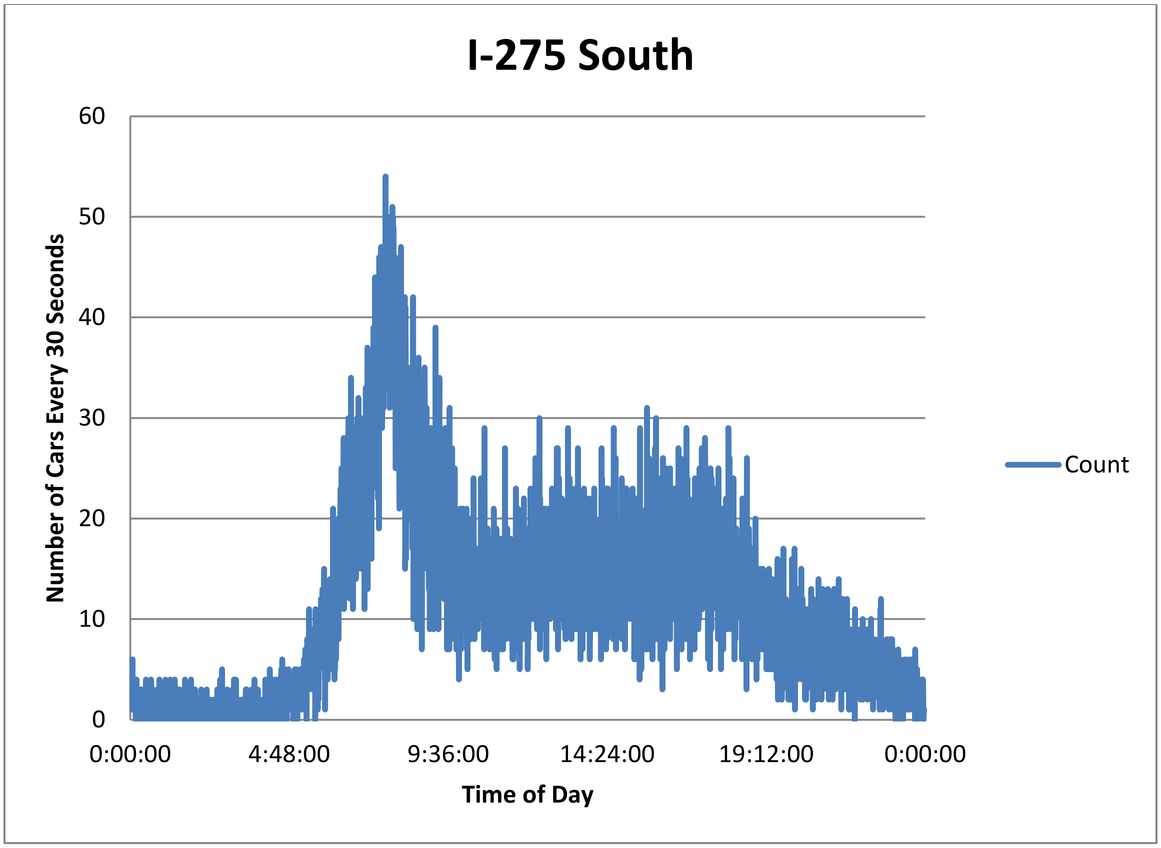

Figure 7: 30 second aggregate traffic volume count for southbound I-275

for the midday period, and 2500-3000 vehicles per hour for the off peak or night period.

The analytical queuing model shows that if capacity is greater than demand, there should be no queuing delay. In some cases, the demand is less than the reduced capacity caused by an incident. For these cases, the analytical queuing model does not accurately reflect the delay found. In these cases, a linear relationship with respect to time was found to be a more accurate representation of the delay calculated for the incident type. A comparison of the estimated reduced capacity to the estimated demand for each matrix cell can be found in Appendix 2.

In order to linearly interpolate the delay, the delay measured was multiplied by the ratio of the average duration of an incident whose delay is unknown divided by the average duration of an incident for which the delay is known. The savings ratios for these linearly interpolated data were different from the savings ratios for the data that used queuing estimates. The savings ratios for the linearly interpolated data were calculated by dividing the time saved due to the TIM program by the average duration of the incident. All of the final values for delay and delay savings that were used in the model can be found in Appendix 3 and Appendix 4 respectively.

Value of Time

The value of time, which is the dollar amount per hour of an individual's time based on their opportunity cost of driving, is needed to calculate the value of delay and is found using the following equation:

$$Value\ of\ Time = (Percent\ Cars \times Average\ Occupancy\ of\ Vehicles \times In\ Vehilce\ Value\ of\ Time) + (Pecent\ Trucks \times Value\ of\ Time\ for\ Trucks) \quad (3.14)$$

The value of time is estimated for different regions of the United States by the Texas Transportation Institute (TTI). The value of time for Knoxville for 2009 was estimated as $16.01 per hour of person travel and $105.67 per hour of truck time (TTI 2009).

Percentages of Vehicles

There were two classes of vehicles used to determine the value of time. These classes were passenger cars and trucks and were the same as TTI's classification of vehicles. Knowing the percentages of trucks and passenger cars in Knoxville is essential for estimating the value of time. The percentage of passenger cars on the interstate is equal to 100 minus the percentage of trucks on the interstate. If one of these percentages known, the other can be found easily. The number of long-haul through trucks on the interstate in Knoxville was assumed to be relatively constant throughout the day and the year because of its location with local truck traffic increasing during peak periods of the day. The volume of truck traffic was roughly twelve million trucks per year or, roughly 33,000 trucks per day which translates into 700 trucks per hour. This volume is supported by data from TDOT and the Federal Highway Administration's (FHWA) Freight Analysis Framework (FAF) (FHWA 2011). A summary of the truck volumes and average annual daily traffic can be found in Appendix 6.

Knoxville is at the intersection of two major interstates, I-75, a major north-south corridor, and I-40, a major east-west corridor. There is a section of roadway in Knoxville where both of these interstate highways are combined, therefore, the truck volume estimates had to be calculated in a way that reflected the difference in the combined traffic, where the interstates are combined and the truck volumes are measured, and the split traffic, where the interstates are separate. To assume that the same number of trucks travelled on the combined I-75 and I-40 corridor as the individual roadways would result in over counting trucks along the roadways when they are separate. Due to TDOT's Smart Fix 40 project, the I-75 corridor and the I-40 corridor were combined along a portion of I-640 while the section of I-40 in downtown Knoxville was under construction. Since the amount of trucks is known along the combined corridors, a proportion of the total would be the appropriate number to assume for each individual interstate after they split at the I-640 and I-75 interchange. The total amount of passenger cars was counted on each roadway but the true proportion of trucks that follow each route was unknown and assumed to be 50% for each direction. One roadway may have a higher proportion of trucks than the other but the total of the proportions is still 100%. This means that the number of trucks at the last place where they shared the roadway is the sum of the two after they have split. Therefore, the total number of trucks on I-640 and the combined I-75 and I-40 corridor was the same as the combined total of trucks on I-75, I-40, and I-640 when the roadways were not combined.

The total truck percentage was calculated as:

$$Truck\ Percentage = \left[(Number\ of\ 100\%\ Truck\ Count\ Locations + \tfrac{1}{2} \times Number\ of\ 50\%\ Truck\ Count\ Locations) \times Number\ of\ Trucks\ per\ day\right] \div [(Number\ of\ 100\%\ Truck\ Count\ Locations + Number\ of\ 50\%\ Truck\ Count\ Locations) \times Total\ Vehicles] \quad (3.17)$$

The number of total vehicles was calculated as the sum of the 2010 TDOT traffic counts whose locations can be seen in figure 8. The traffic counts are from TDOT traffic count locations from the year 2010 and can be found in Appendix 6. The number of trucks had to be adjusted on I-75 and I-40 east of I-640 to reflect

Figure 8. The location of the traffic counts and the locations where truck percentages were assumed to be 50% of the total number of trucks.

the 50% proportional split. The number of total vehicles was counted directly using the data from TDOT, but the number of trucks was assumed to be half of the sum of both roadways.

The total number of vehicles and percentage of trucks were taken for two different days of the year and were found to be similar. One of these days, April 7, 2009, was before the completion of "Smartfix 40" and the second, September 17, 2009, was after.

After finding the values for each of the parameters for value of time, the value of time was calculated for each of the four different categories of time of day as previously defined. Each value of time and its respective components can be found in Table 10.

Value of Delay and Delay Saved

The value of delay is the cost of an incident and represents the money lost due to the total delay to the incident. It is a dollar amount that is quantified by the product of the delay and the value of time and is calculated using the following equation:

$$Value\ of\ Delay = Amount\ of\ Delay\ \times Value\ of\ Time \quad (3.15)$$

The value of delay saved is the dollar amount of savings that were incurred during an incident because of the incident management system. It can be found by multiplying the value of delay and the delay savings ratio as seen in the following equation:

$$Value\ of\ Delay\ Saved = Value\ of\ Delay\ \times Delay\ Savings\ Ratio \quad (3.16)$$

Table 10. Value of time calculations and values for parameters.

Time	Truck Value	Percent Trucks	Passenger Value	Occupancy	Percent Cars	Value of Time
Morning Peak	$100.00	20%	$16.00	1.25	80%	$36.00
Midday	$100.00	20%	$16.00	1.25	80%	$36.00
Afternoon Peak	$100.00	15%	$16.00	1.25	85%	$32.00
Off Peak	$100.00	50%	$16.00	1.25	50%	$60.00

Matrix Model

Once the delay savings and the value of those savings are known, the benefit cost ratio can be calculated. The purpose of the model is to provide the user with an interface that can be manipulated and adjusted depending on local conditions to give a benefit cost ratio that accurately reflects each location. The matrix model consists of three layers with a specific role and function for each layer. Each layer is a separate Microsoft Excel worksheet within the same workbook. The first layer is the input layer, the second is the calculations layer and the third is the savings or output layer. Each layer has sixteen separate matrices that represent the different time and duration categories for the incidents. Within these sixteen matrices are the categories for incident type and location.

Input Layer

The input layer consists of the number of each type of incident. The matrices for this and all layers are the same as the incident log categories. The inputs used in the analysis of Knoxville for 2009 can be found in Appendix 1. This layer can be updated using an incident log to reflect the number of incidents for any year and any location.

Calculations Layer

The calculations layer shows the delay savings calculated for each type of incident. It also has the value of time for each different time period. This layer is adjustable via a ratio factor that changes all the values in a given matrix or the values themselves can be adjusted accordingly. The numbers found for delay savings are very sensitive to changes in capacity and demand and, therefore, delay savings should be recalculated for different years and different regions.

Savings Layer

The savings layer acts as the output because it multiplies the number of incidents of each type by the delay values and the value of time for each type of incident. All 768 cells are filled with a value that represents the total amount of money saved in delay for each type of incident for the whole year. The sum of all the cells is also on this page along with the total costs for the incident management system for that year. The total benefit cost ratio is also calculated on this page.

Model Calibration

The model was calibrated based on the delays for the sample of days with better than 80% data to give the appropriate delays for the Knoxville area for the year 2009. It was calibrated by finding the delay for the sample of incidents and comparing the delay calculated to the theoretical delay values based on the queuing model. Because the theoretical delay savings are highly sensitive to capacity and demand, these numbers had to be adjusted for different incident types to get the closest match of the calculated delays and the theoretical delays.

In order to verify the reasonableness of the delay values used for the cells that were estimated using only theoretical data, the total value of delay calculated using all the data for the year and the total value of the delay calculated by the queuing model were compared. The first step was to find the values of delay for the whole year. This was done by finding the total delay for the days in which 70% of the data were collected for each day. Days with less than 70% of the data available were not included because they were not considered reliable. The reliable days encompassed 238 days for the year 2009. The total delay for these 238 days was about 733,000 hours of delay. This delay includes recurring delay which needed to be subtracted out to find the delay caused by incidents. Because the delay was highly variable from day to day, a thirty day moving average was calculated for 208 of the 238 days. The lowest numbers in delay calculated were assumed to be days with only recurring delay. Therefore, the next step was to move the thirty day moving average values to the lowest delays in order to estimate the recurring delay for each day.

Once the total delay for each of the 208 days was subtracted by the recurring delay, the total incident delay was found to be approximately 325,000 hours of delay. Any negative values were taken to be equal to zero. When extrapolated out to 365 days, this estimate gives a total of 570,000 hours of delay. Appendix 7 contains a graph showing the delay before and after the recurring delay was subtracted out.

Once the total adjusted delay was known for the year, a check of the model-calculated delay values was done to make sure it was similar to the total adjusted delay. The total delay calculated by the model after calibration was about 447,000 hours. This gives a difference of 123,000 hours. The recurring delay was only an estimate; therefore, the calibrated model most likely reflects a conservative estimate of the actual delay for the year.

CHAPTER IV
RESULTS AND DISCUSSION

Results

The third layer of the matrix model is an output page that shows the actual amount of money saved for the year by implementing the traffic incident management program. The analysis for Knoxville, Tennessee shows that the total money in delay savings was $12.1 million in 2009 while the total costs for the year 2009 were $1.43 million. This gives a benefit to cost ratio of 8.5:1 which falls in the lower middle of the range of values calculated by other program reviews.

Currently, the model has been calibrated to reflect the conditions for the year 2009 in Knoxville, Tennessee. The model can be adjusted and used in other places without the need of extensive data collection. The only data needed for adjustments is data on demand, capacity, incident response time, and the equations derived from the queuing model. This model is different from previous models because it relies on real data collected by roadway traffic sensors to calculate delay savings. The model can estimate a benefit cost ratio and can present the savings in a way that shows program managers where and how much delay savings occur and can help in policy decision making.

This model can also be used for reviews of current systems and for planning purposes. If a certain type of incident was producing only a small benefit to the system, this type of incident could be ignored by the incident management program in order to increase the efficiency of the program during times of high activity such as peak hours. If an agency wanted to implement a new TIM program, this model would give them a way to help make decisions about the extent of the program they wish to implement and to help in determining which services they feel would best benefit their area. This model can also be used either macroscopically, as in the Knoxville, Tennessee case study, or for smaller portions of roadways.

Discussion

The benefit cost ratio for Knoxville of 8.5:1 is probably low because it only accounts for delay savings and does not account for safety benefits, environmental impacts, or goodwill. Another reason that it is low is due to the low amount of demand in Knoxville. The amount of delay for an incident is related to the demand at the time of the incident and because the demand is lower in Knoxville than the rest of the nation, it should have lower amounts of delay overall.

Cities with different volumes of demand and different capacities should have different results using this model. For a city like Nashville, Tennessee the demand is higher in more places, but there is also higher capacity infrastructure. Because the capacity is higher, there is typically less relative reduction in capacity due to an incident. However, because the demand is greater, and the queuing equations are more sensitive to changes in demand than capacity, there would still be a gain in the delay savings. This is reflected by a sensitivity analysis of the delay equations that can be found in Appendix 8

A tool to adjust this model for use in other places has been included in the model itself in the form of a ratio multiplier which is included on the calculations page. This can be used to adjust for the amount of delay difference from one place to the next. A simple ratio of the difference in delay savings for each of the sixteen matrices can be input into the calculations page. This ratio would represent the difference between delay savings due to capacity and demand changes in different areas. The ratio can also be used as a quick adjustment to the delay savings ratios to reflect changes in assumed incident response times for various parameters.

Some of the incidents are not represented well in this analysis. For instance, a car can be abandoned on the interstate and the job of the HELP trucks is to assist the police in tagging these vehicles with the date discovered. Once the vehicle is tagged it is allowed to sit on the side of the road for up to forty-eight hours. An extended comparison was not made for abandoned cars for forty-eight hours because most of the abandoned cars were cleared before this time and if an extended analysis was made, the error in the delay calculated would likely be increased as compared to the shorter analysis.

Many of the days analyzed initially showed low amounts of delay with the exception being accidents and vehicle fires. When the days were compared with an alternate day, they sometimes showed less delay on the days when the incident occurred. This can be explained by daily variances in traffic patterns and by the lack of knowledge of what is actually occurring on each particular day. For instance, an accident could occur at the same spot there was an abandoned vehicle the previous day. If the abandoned vehicle delay data were compared to the delay data for the day with an accident, there is a large chance that the delay for the day of the abandoned vehicle would be much less than the delay data for the day with the accident. In these cases, where the delay for an incident was less than a corresponding similar day, additional days beyond just the following or next similar day were analyzed in order to understand what the true baseline delay was for that area. In instances where the corresponding similar days had a majority of similar day's delay being greater than the day with the incident being studied, the delay was recorded as zero.

The data were collected at times during Smart Fix 40 and after the completion of Smart Fix 40. However, the delay data were not affected by this project because the interstates in Knoxville had more lane consistency with the project in place and most of the data used were from the time that Smart Fix 40 occurred. Another way the data were not affected by Smart Fix 40 was by not using the delay at stations on I-40 between the I-640 interchanges in the sample of incidents, and therefore, excluding the unusually low volumes of traffic along this stretch of I-40 during Smart Fix 40. Another consistency exhibited by the data before and after Smart Fix 40 was that the volume of traffic and the percentage of trucks were calculated for days during and after the Smart Fix 40 project and were found to be similar.

The benefit cost ratio found for SmartWay in Knoxville is only reflective of the conditions experienced in 2009 but can be adjusted for any other year. The model can be adjusted to reflect different capacity and demand values and should be done so for future analyses in Knoxville.

Future research could build on this model by calculating other types of benefits such as secondary crashes avoided and other safety benefits. Public perception could also be included in future models. Further research in demand and capacity analysis could change the way this model functions but it can be adjusted to reflect these changes.

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APPENDIX

Appendix 1

Numbers used for the input page of the model. Time 1 indicates Morning Peak, Time 2 is Midday, Time 3 is Afternoon Peak, and Time 4 is Off Peak. Druation 1 is less than one hour, Duration 2 is 1 to 3 hours, Duration 3 is 3 to 5 hours, and Duration 4 is greater than 5 hours.

TIME 1, DURATION 1						
CAUSE	LOCATION					
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median
Accident	193	17	7			17
Vehicle Fire	4	1				0
Disabled	1486	181	51	7		97
Abandoned	511	172	29	9		58
Debris	266	27	6	1		14
Pedestrian	2					1
Other	170	13	6	2		19
No Note	11	2				0

TIME 1, DURATION 2						
CAUSE	LOCATION					
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median
Accident	13					1
Vehicle Fire	1					
Disabled	7	4				
Abandoned	1			1		
Debris						
Pedestrian						
Other	1					
No Note						

TIME 1, DURATION 3						
CAUSE	LOCATION					
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median
Accident	2					
Vehicle Fire						
Disabled		1				
Abandoned						
Debris						
Pedestrian						
Other						
No Note						

TIME 1, DURATION 4						
CAUSE	LOCATION					
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median
Accident						
Vehicle Fire						
Disabled	1					
Abandoned						
Debris						
Pedestrian						
Other						
No Note						

TIME 2, DURATION 1						
CAUSE	LOCATION					
	Shoulder	One Lane	Two Lanes	Three Lanes	4 or More	Median
Accident	70	114	54	6	1	44
Vehicle Fire	7	7	2	1		
Disabled	2724	97	15	1		223
Abandoned	773	9				23
Debris	25	483	108	21	3	27
Pedestrian	2					
Other	412	68	8	15	8	20
No Note	2	1	1	1		1

TIME 2, DURATION 2						
CAUSE	LOCATION					
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median
Accident	3	10	7	3	3	
Vehicle Fire				1		
Disabled	11	3		1		
Abandoned	3					
Debris			2		1	2
Pedestrian						
Other			1	1		
No Note	1	2				1

TIME 2, DURATION 3						
CAUSE	LOCATION					
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median
Accident	1					
Vehicle Fire						
Disabled	2	1				
Abandoned						
Debris			1			
Pedestrian						
Other						
No Note						

TIME 2, DURATION 4						
CAUSE	LOCATION					
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median
Accident		1				
Vehicle Fire						
Disabled	2					
Abandoned						
Debris						
Pedestrian						
Other						
No Note						

TIME 3, DURATION 1						
CAUSE	LOCATION					
	Shoulder	One Lane	Two Lanes	Three Lanes	4 or More	Median
Accident	102	133	69	15		47
Vehicle Fire	2	5	1	1		1
Disabled	2565	105	5			236
Abandoned	463	8				13
Debris	28	282	67	11	1	12
Pedestrian	1					
Other	290	9	4	1		20
No Note						

TIME 3, DURATION 2						
CAUSE	LOCATION					
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median
Accident	2	6	4	1	1	2
Vehicle Fire						
Disabled	14					2
Abandoned						
Debris			1			
Pedestrian						
Other		1	1			
No Note						

TIME 3, DURATION 3						
CAUSE	LOCATION					
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median
Accident						
Vehicle Fire						
Disabled	1		1			
Abandoned						
Debris						
Pedestrian						
Other		3				1
No Note						

TIME 3, DURATION 4						
CAUSE	LOCATION					
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median
Accident						
Vehicle Fire						
Disabled						
Abandoned						
Debris						
Pedestrian						
Other		1				
No Note						

TIME 4, DURATION 1						
CAUSE	LOCATION					
	Shoulder	One Lane	Two Lanes	Three Lanes	4 or More	Median
Accident	32	35	24	6	1	20
Vehicle Fire	3	1	3			
Disabled	816	47	3			59
Abandoned	260	2				5
Debris	11	87	21	2		6
Pedestrian	1					
Other	69	9	2	2	1	7
No Note		1	1			

TIME 4, DURATION 2						
CAUSE	LOCATION					
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median
Accident	2	4	5	2	1	1
Vehicle Fire						
Disabled	2	3				1
Abandoned		1				
Debris						
Pedestrian						
Other		3	1			
No Note						

TIME 4, DURATION 3						
CAUSE	LOCATION					
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median
Accident			1			
Vehicle Fire						
Disabled		1				
Abandoned						
Debris						
Pedestrian						
Other						
No Note						

TIME 4, DURATION 4						
CAUSE	LOCATION					
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median
Accident				1		
Vehicle Fire						
Disabled	2	1				
Abandoned						
Debris						
Pedestrian						
Other	2		2		1	
No Note						

Appendix 2

Test results showing when to use linear interpolation versus the queuing diagram.

For time periods 1 and 3 where capacity is 6000 vehicles per hour and demand is 5000 vehicles per hour.

Cause	Location					
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median
Blocking	Linear	Queuing	Queuing	Queuing	Queuing	Queuing
Non-Blocking	Queuing	Queuing	Queuing	Queuing	Queuing	Queuing

Reduced capacity estimates for time periods 1 and 3.

Cause	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median
Blocking	0.85	0.6	0.3	0.15	0	0.8
Non-Blocking	0.8325	0.8317	0.8	0.6667	0.5	0.8317

For time period 2 where capacity is 6000 vehicles per hour and demand is 4500 vehicles per hour.

Cause	Location					
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median
Blocking	Linear	Queuing	Queuing	Queuing	Queuing	Linear
Non-Blocking	Linear	Linear	Linear	Queuing	Queuing	Linear

Reduced capacity estimates for time period 2

Cause	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median
Blocking	0.85	0.6	0.3	0.15	0	0.8
Non-Blocking	0.8325	0.8317	0.8	0.6667	0.5	0.8317

For time period 4 where capacity is 6000 vehicles per hour and demand is 3000 vehicles per hour.

Cause	Location					
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median
Blocking	Linear	Linear	Queuing	Queuing	Queuing	Linear
Non-Blocking	Linear	Linear	Linear	Linear	Linear	Linear

Reduced capacity estimates for time period 4

Cause	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median
Blocking	0.85	0.6	0.25	0.15	0	0.8
Non-Blocking	0.8325	0.8317	0.8	0.6667	0.5	0.8317

Appendix 3

Values of delay used in the model.

TIME 1, DURATION 1							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median	Value of Time
Accident	5.4	58.05	1289.3	2343.6	3690.9	10.8	$36.00
Vehicle Fire	13.5	526.5	3164.4	5273.1	7909.7	27	
Disabled	1.35	2.7	63.45	527.85	1582.2	2.7	
Abandoned	1.35	2.7	63.45	527.85	1582.2	2.7	
Debris	1.35	2.7	63.45	527.85	1582.2	2.7	
Pedestrian	1.35	2.7	63.45	527.85	1582.2	2.7	
Other	1.35	2.7	63.45	527.85	1582.2	2.7	
No Note	1.35	2.7	63.45	527.85	1582.2	2.7	
Ratio	1						

TIME 1, DURATION 2							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median	Value of Time
Accident	14.4	159.84	3519.7	6399.7	10080	29.88	$36.00
Vehicle Fire	37.8	1440	8640	14400	21600	79.2	
Disabled	3.6	7.2	172.8	1440	4320	7.2	
Abandoned	3.6	7.2	172.8	1440	4320	7.2	
Debris	3.6	7.2	172.8	1440	4320	7.2	
Pedestrian	3.6	7.2	172.8	1440	4320	7.2	
Other	3.6	7.2	172.8	1440	4320	7.2	
No Note	3.6	7.2	172.8	1440	4320	7.2	
Ratio	1						

TIME 1, DURATION 3							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median	Value of Time
Accident	28.525	310.98	6844.4	12444	19600	58.275	$36.00
Vehicle Fire	73.5	2800	16800	28000	42000	154	
Disabled	7	14	336	2800	8400	14	
Abandoned	7	14	336	2800	8400	14	
Debris	7	14	336	2800	8400	14	
Pedestrian	7	14	336	2800	8400	14	
Other	7	14	336	2800	8400	14	
No Note	7	14	336	2800	8400	14	
Ratio	1						

TIME 1, DURATION 4							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median	Value of Time
Accident	41.838	456	10032	18240	28728	85.272	$36.00
Vehicle Fire	107.73	4104	24624	41040	61560	225.72	
Disabled	10.26	20.52	492.48	4104	12312	20.52	
Abandoned	10.26	20.52	492.48	4104	12312	20.52	
Debris	10.26	20.52	492.48	4104	12312	20.52	
Pedestrian	10.26	20.52	492.48	4104	12312	20.52	
Other	10.26	20.52	492.48	4104	12312	20.52	
No Note	10.26	20.52	492.48	4104	12312	20.52	
Ratio	1						

TIME 2, DURATION 1							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	4 or More	Median	Value of Time
Accident	2.1333	27	351.56	878.91	1582	4.2666	$36.00
Vehicle Fire	4.2666	175.5	1757.7	3075.3	4746.6	10.667	
Disabled	0.5333	1.0667	1.6667	175.5	791.1	1.0667	
Abandoned	0.5333	1.0667	1.6667	175.5	791.1	1.0667	
Debris	0.5333	1.0667	1.6667	175.5	791.1	1.0667	
Pedestrian	0.5333	1.0667	1.6667	175.5	791.1	1.0667	
Other	0.5333	1.0667	1.6667	175.5	791.1	1.0667	
No Note	0.5333	1.0667	1.6667	175.5	791.1	1.0667	
Ratio	1						

TIME 2, DURATION 2							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median	Value of Time
Accident	2.1333	74.88	960	2400	4320	4.2666	$36.00
Vehicle Fire	4.2666	74.88	960	2400	4320	10.667	
Disabled	0.5333	1.0667	5.3333	479.88	2160	1.0667	
Abandoned	0.5333	1.0667	5.3333	479.88	2160	1.0667	
Debris	0.5333	1.0667	5.3333	479.88	2160	1.0667	
Pedestrian	0.5333	1.0667	5.3333	479.88	2160	1.0667	
Other	0.5333	1.0667	5.3333	479.88	2160	1.0667	
No Note	0.5333	1.0667	5.3333	479.88	2160	1.0667	
Ratio	1						

TIME 2, DURATION 3							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median	Value of Time
Accident	2.1333	145.78	1866.7	4666.7	8400	4.2666	$36.00
Vehicle Fire	4.2666	145.78	1866.7	4666.7	8400	10.667	
Disabled	0.5333	1.0667	5.3333	933.28	4200	1.0667	
Abandoned	0.5333	1.0667	5.3333	933.28	4200	1.0667	
Debris	0.5333	1.0667	5.3333	933.28	4200	1.0667	
Pedestrian	0.5333	1.0667	5.3333	933.28	4200	1.0667	
Other	0.5333	1.0667	5.3333	933.28	4200	1.0667	
No Note	0.5333	1.0667	5.3333	933.28	4200	1.0667	
Ratio	1						

TIME 2, DURATION 4							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median	Value of Time
Accident	2.1333	213.75	2736	6840	12312	4.2666	$36.00
Vehicle Fire	4.2666	213.75	2736	6840	12312	10.667	
Disabled	0.5333	1.0667	5.3333	1368	6156	1.0667	
Abandoned	0.5333	1.0667	5.3333	1368	6156	1.0667	
Debris	0.5333	1.0667	5.3333	1368	6156	1.0667	
Pedestrian	0.5333	1.0667	5.3333	1368	6156	1.0667	
Other	0.5333	1.0667	5.3333	1368	6156	1.0667	
No Note	0.5333	1.0667	5.3333	1368	6156	1.0667	
Ratio	1						

TIME 3, DURATION 1							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	4 or More	Median	Value of Time
Accident	5.4	58.05	1289.3	2343.6	3690.9	10.8	$32.00
Vehicle Fire	13.5	526.5	3164.4	5273.1	7909.7	27	
Disabled	1.35	2.7	63.45	527.85	1582.2	2.7	
Abandoned	1.35	2.7	63.45	527.85	1582.2	2.7	
Debris	1.35	2.7	63.45	527.85	1582.2	2.7	
Pedestrian	1.35	2.7	63.45	527.85	1582.2	2.7	
Other	1.35	2.7	63.45	527.85	1582.2	2.7	
No Note	1.35	2.7	63.45	527.85	1582.2	2.7	
Ratio	1						

TIME 3, DURATION 2							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median	Value of Time
Accident	14.4	159.84	3519.7	6399.7	10080	29.88	$32.00
Vehicle Fire	37.8	1440	8640	14400	21600	79.2	
Disabled	1.152	2.304	172.8	1440	4320	2.304	
Abandoned	1.152	2.304	172.8	1440	4320	2.304	
Debris	1.152	2.304	172.8	1440	4320	2.304	
Pedestrian	1.152	2.304	172.8	1440	4320	2.304	
Other	1.152	2.304	172.8	1440	4320	2.304	
No Note	1.152	2.304	172.8	1440	4320	2.304	
Ratio	1						

TIME 3, DURATION 3							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median	Value of Time
Accident	28.525	310.98	6844.4	12444	19600	58.275	$32.00
Vehicle Fire	73.5	2800	16800	28000	42000	154	
Disabled	1.12	2.24	336	2800	8400	2.24	
Abandoned	1.12	2.24	336	2800	8400	2.24	
Debris	1.12	2.24	336	2800	8400	2.24	
Pedestrian	1.12	2.24	336	2800	8400	2.24	
Other	1.12	2.24	336	2800	8400	2.24	
No Note	1.12	2.24	336	2800	8400	2.24	
Ratio	1						

TIME 3, DURATION 4							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median	Value of Time
Accident	41.838	456	10032	18240	28728	85.272	$32.00
Vehicle Fire	107.73	4104	24624	41040	61560	225.72	
Disabled	1.0944	2.1888	492.48	4104	12312	2.1888	
Abandoned	1.0944	2.1888	492.48	4104	12312	2.1888	
Debris	1.0944	2.1888	492.48	4104	12312	2.1888	
Pedestrian	1.0944	2.1888	492.48	4104	12312	2.1888	
Other	1.0944	2.1888	492.48	4104	12312	2.1888	
No Note	1.0944	2.1888	492.48	4104	12312	2.1888	
Ratio	1						

TIME 4, DURATION 1							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	4 or More	Median	Value of Time
Accident	2.1333	8.1	151.2	565.65	1130	4.2666	$60.00
Vehicle Fire	4.2666	10.8	151.2	565.65	1130	8.5333	
Disabled	0.5333	1.0667	1.0667	5.3333	10.667	1.0667	
Abandoned	0.5333	1.0667	1.0667	5.3333	10.667	1.0667	
Debris	0.5333	1.0667	1.0667	5.3333	10.667	1.0667	
Pedestrian	0.5333	1.0667	1.0667	5.3333	10.667	1.0667	
Other	0.5333	1.0667	1.0667	5.3333	10.667	1.0667	
No Note	0.5333	1.0667	1.0667	5.3333	10.667	1.0667	
Ratio	1						

TIME 4, DURATION 2							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median	Value of Time
Accident	2.1333	6.912	411.48	1543	3085.6	4.2666	$60.00
Vehicle Fire	4.2666	9.216	411.48	1543	3085.6	8.5333	
Disabled	0.5333	1.0667	1.0667	5.3333	10.667	1.0667	
Abandoned	0.5333	1.0667	1.0667	5.3333	10.667	1.0667	
Debris	0.5333	1.0667	1.0667	5.3333	10.667	1.0667	
Pedestrian	0.5333	1.0667	1.0667	5.3333	10.667	1.0667	
Other	0.5333	1.0667	1.0667	5.3333	10.667	1.0667	
No Note	0.5333	1.0667	1.0667	5.3333	10.667	1.0667	
Ratio	1						

TIME 4, DURATION 3							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median	Value of Time
Accident	2.1333	6.72	799.93	3000	6000.1	4.2666	$60.00
Vehicle Fire	4.2666	8.96	799.93	3000	6000.1	8.5333	
Disabled	0.5333	1.0667	1.0667	5.3333	10.667	1.0667	
Abandoned	0.5333	1.0667	1.0667	5.3333	10.667	1.0667	
Debris	0.5333	1.0667	1.0667	5.3333	10.667	1.0667	
Pedestrian	0.5333	1.0667	1.0667	5.3333	10.667	1.0667	
Other	0.5333	1.0667	1.0667	5.3333	10.667	1.0667	
No Note	0.5333	1.0667	1.0667	5.3333	10.667	1.0667	
Ratio	1						

TIME 4, DURATION 4							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median	Value of Time
Accident	2.1333	6.5664	1172.6	4397.1	8794.3	4.2666	$60.00
Vehicle Fire	4.2666	8.7552	1172.6	4397.1	8794.3	8.5332	
Disabled	0.5333	1.0667	1.0667	5.3333	10.667	1.0667	
Abandoned	0.5333	1.0667	1.0667	5.3333	10.667	1.0667	
Debris	0.5333	1.0667	1.0667	5.3333	10.667	1.0667	
Pedestrian	0.5333	1.0667	1.0667	5.3333	10.667	1.0667	
Other	0.5333	1.0667	1.0667	5.3333	10.667	1.0667	
No Note	0.5333	1.0667	1.0667	5.3333	10.667	1.0667	
Ratio	1						

Appendix 4

Delay savings calculated by the model.

TIME 1, DURATION 1							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median	TOTAL
Accident	$37,519.20	$35,526.60	$324,891.00	$0.00	$0.00	$6,609.60	$404,546.40
Vehicle Fire	$1,944.00	$18,954.00	$0.00	$0.00	$0.00	$0.00	$20,898.00
Disabled	$72,219.60	$17,593.20	$116,494.20	$133,018.20	$0.00	$9,428.40	$348,753.60
Abandoned	$24,834.60	$16,718.40	$66,241.80	$171,023.40	$0.00	$5,637.60	$284,455.80
Debris	$12,927.60	$2,624.40	$13,705.20	$19,002.60	$0.00	$1,360.80	$49,620.60
Pedestrian	$97.20	$0.00	$0.00	$0.00	$0.00	$97.20	$194.40
Other	$8,262.00	$1,263.60	$13,705.20	$38,005.20	$0.00	$1,846.80	$63,082.80
No Note	$534.60	$194.40	$0.00	$0.00	$0.00	$0.00	$729.00
TOTAL	$158,338.80	$92,874.60	$535,037.40	$361,049.40	$0.00	$24,980.40	$1,172,280.60

TIME 1, DURATION 2							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median	TOTAL
Accident	$6,739.20	$0.00	$0.00	$0.00	$0.00	$1,075.68	$7,814.88
Vehicle Fire	$1,360.80	$0.00	$0.00	$0.00	$0.00	$0.00	$1,360.80
Disabled	$907.20	$1,036.80	$0.00	$0.00	$0.00	$0.00	$1,944.00
Abandoned	$129.60	$0.00	$0.00	$51,840.00	$0.00	$0.00	$51,969.60
Debris	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Pedestrian	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Other	$129.60	$0.00	$0.00	$0.00	$0.00	$0.00	$129.60
No Note	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
TOTAL	$9,266.40	$1,036.80	$0.00	$51,840.00	$0.00	$1,075.68	$63,218.88

TIME 1, DURATION 3							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median	TOTAL
Accident	$2,053.80	$0.00	$0.00	$0.00	$0.00	$0.00	$2,053.80
Vehicle Fire	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Disabled	$0.00	$504.00	$0.00	$0.00	$0.00	$0.00	$504.00
Abandoned	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Debris	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Pedestrian	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Other	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
No Note	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
TOTAL	$2,053.80	$504.00	$0.00	$0.00	$0.00	$0.00	$2,557.80

TIME 1, DURATION 4							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median	TOTAL
Accident	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Vehicle Fire	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Disabled	$369.36	$0.00	$0.00	$0.00	$0.00	$0.00	$369.36
Abandoned	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Debris	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Pedestrian	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Other	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
No Note	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
TOTAL	$369.36	$0.00	$0.00	$0.00	$0.00	$0.00	$369.36

TIME 2, DURATION 1							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	4 or More	Median	TOTAL
Accident	$5,375.97	$110,808.00	$683,437.50	$189,843.75	$56,953.13	$6,758.36	$1,053,176.70
Vehicle Fire	$1,075.19	$44,226.00	$126,554.40	$110,710.80	$0.00	$0.00	$282,566.39
Disabled	$52,300.47	$3,724.78	$900.00	$6,318.00	$0.00	$8,563.15	$71,806.39
Abandoned	$14,841.51	$345.60	$0.00	$0.00	$0.00	$883.19	$16,070.30
Debris	$480.00	$18,547.08	$6,479.97	$132,678.00	$85,438.80	$1,036.79	$244,660.65
Pedestrian	$38.40	$0.00	$0.00	$0.00	$0.00	$0.00	$38.40
Other	$7,910.35	$2,611.18	$480.00	$94,770.00	$227,836.80	$768.00	$334,376.33
No Note	$38.40	$38.40	$60.00	$6,318.00	$0.00	$38.40	$6,493.20
TOTAL	$82,060.29	$180,301.04	$817,911.87	$540,638.55	$370,228.73	$18,047.89	$2,009,188.36

TIME 2, DURATION 2							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median	TOTAL
Accident	$230.40	$26,956.80	$241,920.00	$259,200.00	$466,560.00	$0.00	$994,867.20
Vehicle Fire	$0.00	$0.00	$0.00	$86,400.00	$0.00	$0.00	$86,400.00
Disabled	$211.20	$115.20	$0.00	$17,275.68	$0.00	$0.00	$17,602.08
Abandoned	$57.60	$0.00	$0.00	$0.00	$0.00	$0.00	$57.60
Debris	$0.00	$0.00	$384.00	$0.00	$77,760.00	$76.80	$78,220.80
Pedestrian	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Other	$0.00	$0.00	$192.00	$17,275.68	$0.00	$0.00	$17,467.68
No Note	$19.20	$76.80	$0.00	$0.00	$0.00	$38.40	$134.40
TOTAL	$518.40	$27,148.80	$242,496.00	$380,151.36	$544,320.00	$115.20	$1,194,749.75

TIME 2, DURATION 3							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median	TOTAL
Accident	$76.80	$0.00	$0.00	$0.00	$0.00	$0.00	$76.80
Vehicle Fire	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Disabled	$38.40	$38.40	$0.00	$0.00	$0.00	$0.00	$76.80
Abandoned	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Debris	$0.00	$0.00	$192.00	$0.00	$0.00	$0.00	$192.00
Pedestrian	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Other	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
No Note	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
TOTAL	$115.20	$38.40	$192.00	$0.00	$0.00	$0.00	$345.60

TIME 2, DURATION 4							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median	TOTAL
Accident	$0.00	$7,695.00	$0.00	$0.00	$0.00	$0.00	$7,695.00
Vehicle Fire	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Disabled	$38.40	$0.00	$0.00	$0.00	$0.00	$0.00	$38.40
Abandoned	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Debris	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Pedestrian	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Other	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
No Note	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
TOTAL	$38.40	$7,695.00	$0.00	$0.00	$0.00	$0.00	$7,733.40

TIME 3, DURATION 1							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	4 or More	Median	TOTAL
Accident	$17,625.60	$247,060.80	$2,846,664.00	$1,124,928.00	$0.00	$16,243.20	$4,252,521.60
Vehicle Fire	$864.00	$84,240.00	$101,260.80	$168,739.20	$0.00	$864.00	$355,968.00
Disabled	$110,808.00	$9,072.00	$10,152.00	$0.00	$0.00	$20,390.40	$150,422.40
Abandoned	$20,001.60	$691.20	$0.00	$0.00	$0.00	$1,123.20	$21,816.00
Debris	$1,209.60	$24,364.80	$136,036.80	$185,803.20	$50,630.40	$1,036.80	$399,081.60
Pedestrian	$43.20	$0.00	$0.00	$0.00	$0.00	$0.00	$43.20
Other	$12,528.00	$777.60	$8,121.60	$16,891.20	$0.00	$1,728.00	$40,046.40
No Note	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
TOTAL	$163,080.00	$366,206.40	$3,102,235.20	$1,496,361.60	$50,630.40	$41,385.60	$5,219,899.20

TIME 3, DURATION 2							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median	TOTAL
Accident	$921.60	$30,689.28	$450,524.16	$204,791.04	$322,560.00	$1,912.32	$1,011,398.40
Vehicle Fire	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Disabled	$516.10	$0.00	$0.00	$0.00	$0.00	$147.46	$663.55
Abandoned	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Debris	$0.00	$0.00	$5,529.60	$0.00	$0.00	$0.00	$5,529.60
Pedestrian	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Other	$0.00	$73.73	$5,529.60	$0.00	$0.00	$0.00	$5,603.33
No Note	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
TOTAL	$1,437.70	$30,763.01	$461,583.36	$204,791.04	$322,560.00	$2,059.78	$1,023,194.88

TIME 3, DURATION 3							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median	TOTAL
Accident	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Vehicle Fire	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Disabled	$35.84	$0.00	$10,752.00	$0.00	$0.00	$0.00	$10,787.84
Abandoned	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Debris	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Pedestrian	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Other	$0.00	$215.04	$0.00	$0.00	$0.00	$71.68	$286.72
No Note	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
TOTAL	$35.84	$215.04	$10,752.00	$0.00	$0.00	$71.68	$11,074.56

TIME 3, DURATION 4							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median	TOTAL
Accident	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Vehicle Fire	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Disabled	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Abandoned	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Debris	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Pedestrian	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Other	$0.00	$70.04	$0.00	$0.00	$0.00	$0.00	$70.04
No Note	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
TOTAL	$0.00	$70.04	$0.00	$0.00	$0.00	$0.00	$70.04

TIME 4, DURATION 1							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	4 or More	Median	TOTAL
Accident	$4,095.97	$17,010.00	$217,728.00	$203,634.00	$67,797.00	$5,119.97	$515,384.94
Vehicle Fire	$768.00	$648.00	$27,216.00	$0.00	$0.00	$0.00	$28,632.00
Disabled	$26,111.84	$3,007.98	$192.00	$0.00	$0.00	$3,775.98	$33,087.79
Abandoned	$8,319.95	$128.00	$0.00	$0.00	$0.00	$320.00	$8,767.95
Debris	$352.00	$5,567.97	$1,343.99	$640.00	$0.00	$384.00	$8,287.95
Pedestrian	$32.00	$0.00	$0.00	$0.00	$0.00	$0.00	$32.00
Other	$2,207.99	$576.00	$128.00	$640.00	$640.00	$448.00	$4,639.97
No Note	$0.00	$64.00	$64.00	$0.00	$0.00	$0.00	$128.00
TOTAL	$41,887.74	$27,001.94	$246,671.99	$204,913.99	$68,437.00	$10,047.94	$598,960.59

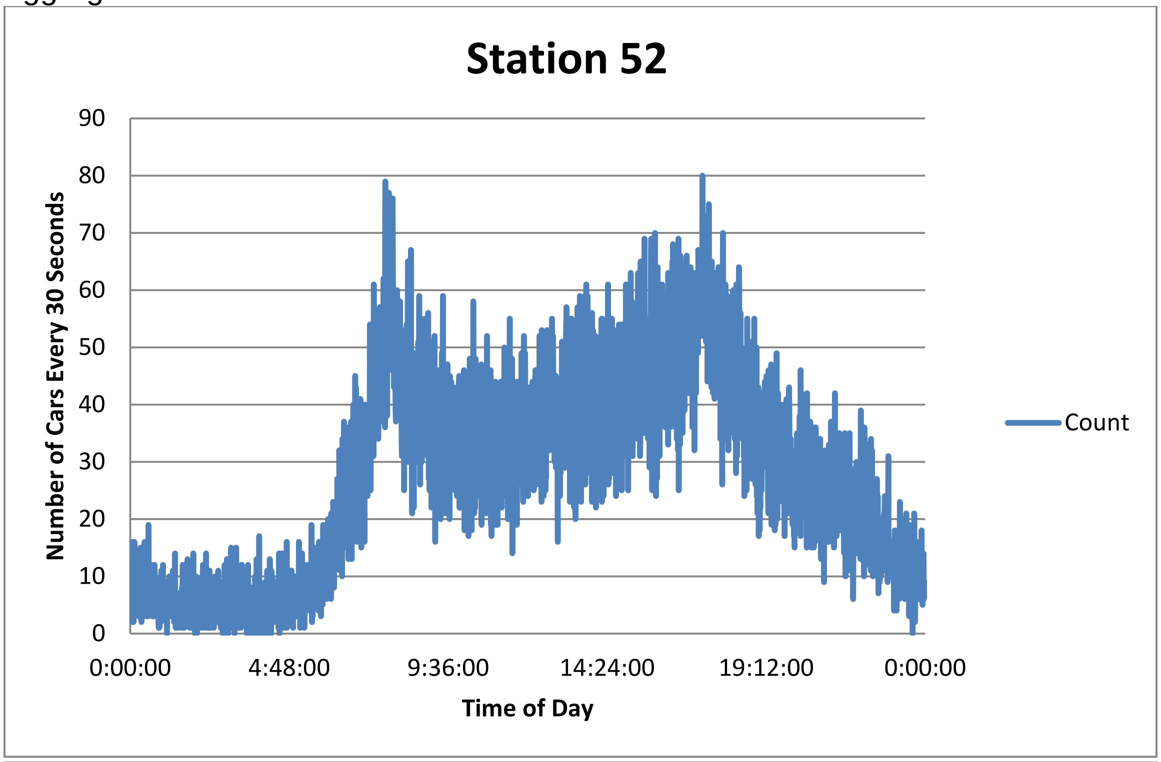
TIME 4, DURATION 2							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median	TOTAL
Accident	$256.00	$1,658.88	$123,444.00	$185,155.20	$185,133.60	$256.00	$495,903.68
Vehicle Fire	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Disabled	$64.00	$192.00	$0.00	$0.00	$0.00	$64.00	$320.00
Abandoned	$0.00	$64.00	$0.00	$0.00	$0.00	$0.00	$64.00
Debris	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Pedestrian	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Other	$0.00	$192.00	$64.00	$0.00	$0.00	$0.00	$256.00
No Note	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
TOTAL	$320.00	$2,106.88	$123,508.00	$185,155.20	$185,133.60	$320.00	$496,543.68

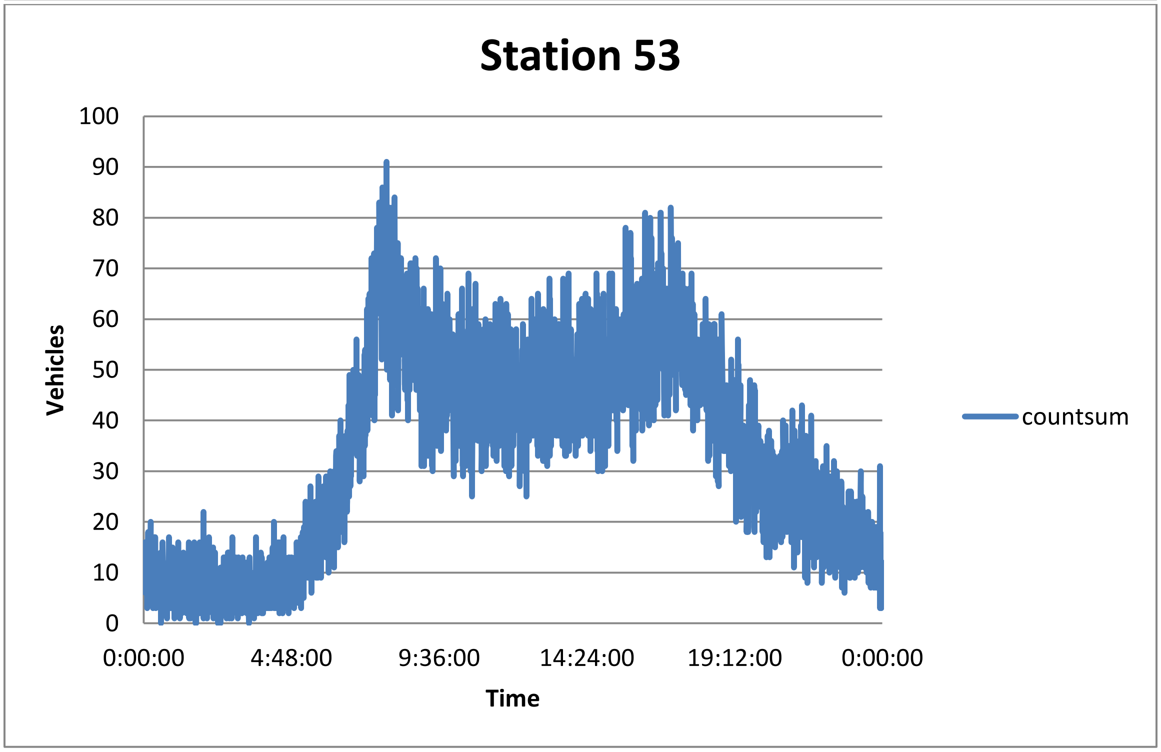
TIME 4, DURATION 3							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median	TOTAL
Accident	$0.00	$0.00	$47,995.50	$0.00	$0.00	$0.00	$47,995.50
Vehicle Fire	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Disabled	$0.00	$64.00	$0.00	$0.00	$0.00	$0.00	$64.00
Abandoned	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Debris	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Pedestrian	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Other	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
No Note	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
TOTAL	$0.00	$64.00	$47,995.50	$0.00	$0.00	$0.00	$48,059.50

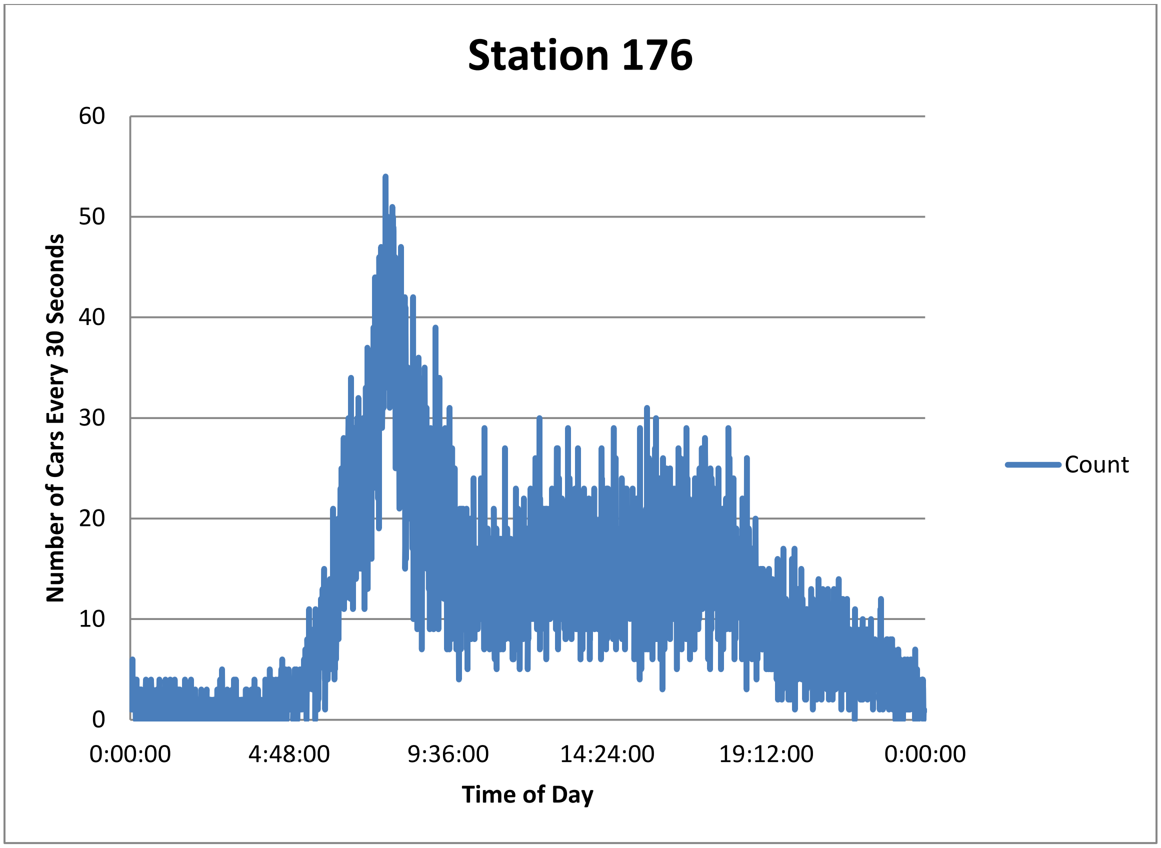
TIME 4, DURATION 4							
CAUSE	LOCATION						
	Shoulder	One Lane	Two Lanes	Three Lanes	All Lanes	Median	TOTAL
Accident	$0.00	$0.00	$0.00	$263,825.64	$0.00	$0.00	$263,825.64
Vehicle Fire	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Disabled	$64.00	$64.00	$0.00	$0.00	$0.00	$0.00	$128.00
Abandoned	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Debris	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Pedestrian	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Other	$64.00	$0.00	$128.00	$0.00	$639.99	$0.00	$831.99
No Note	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
TOTAL	$128.00	$64.00	$128.00	$263,825.64	$639.99	$0.00	$264,785.63

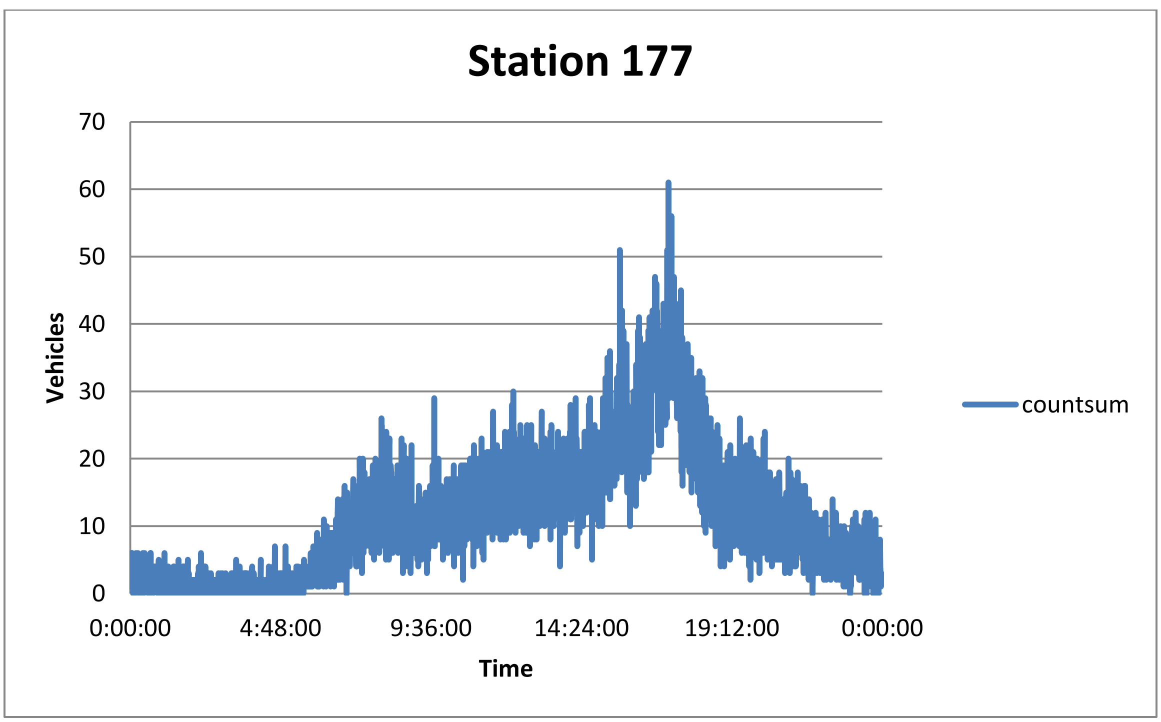
Appendix 5

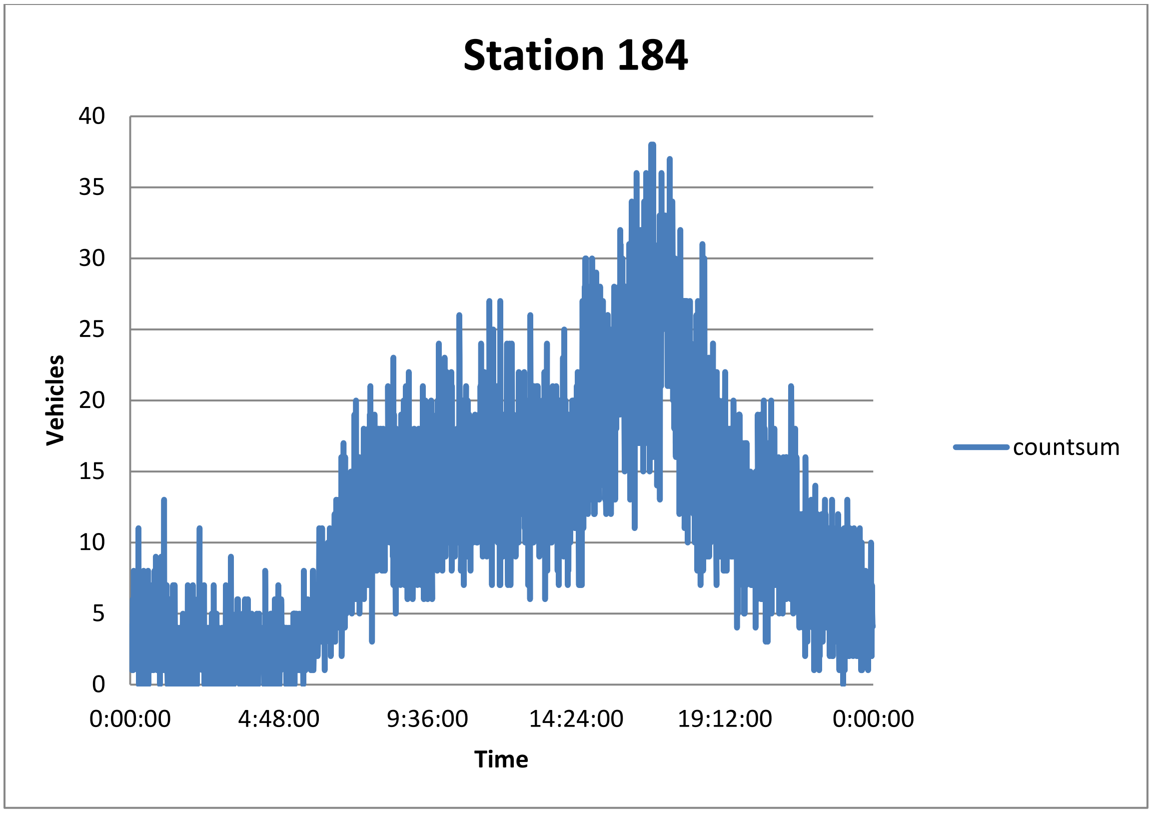
Graphs showing number of vehicles at selected locations for thirty second aggregate data.

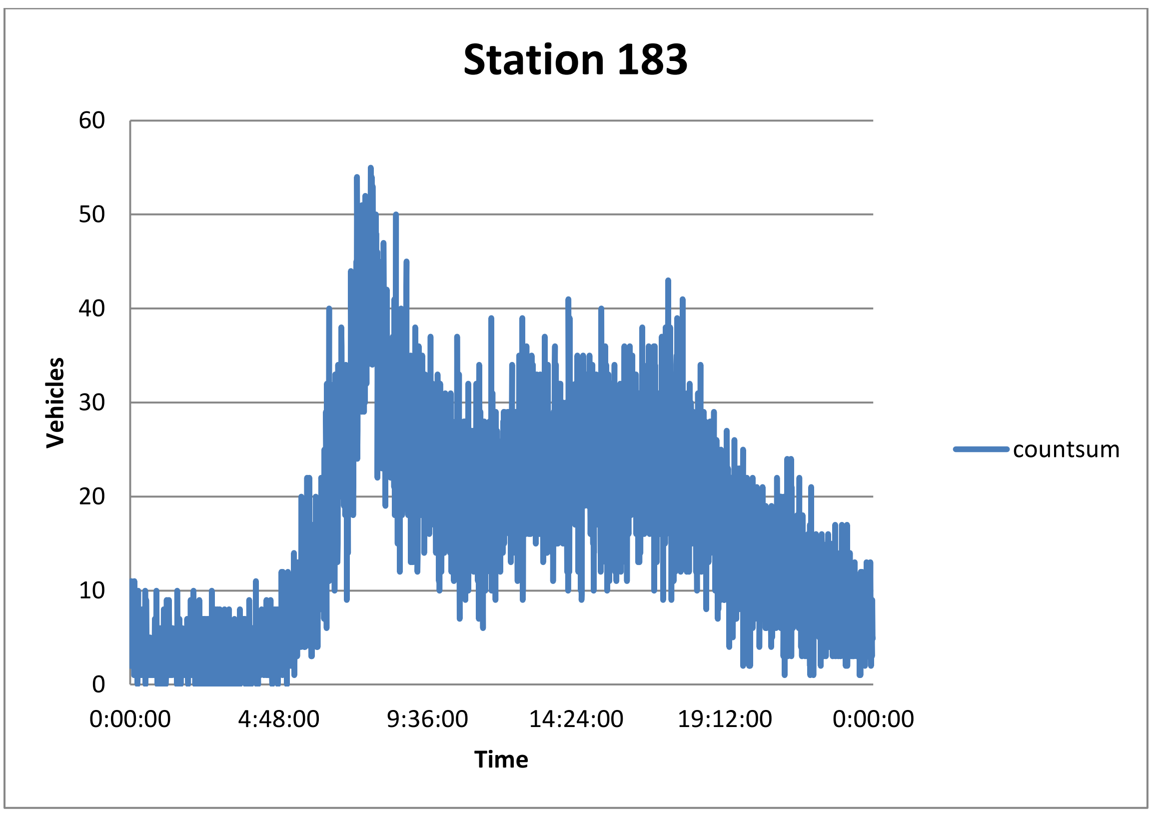


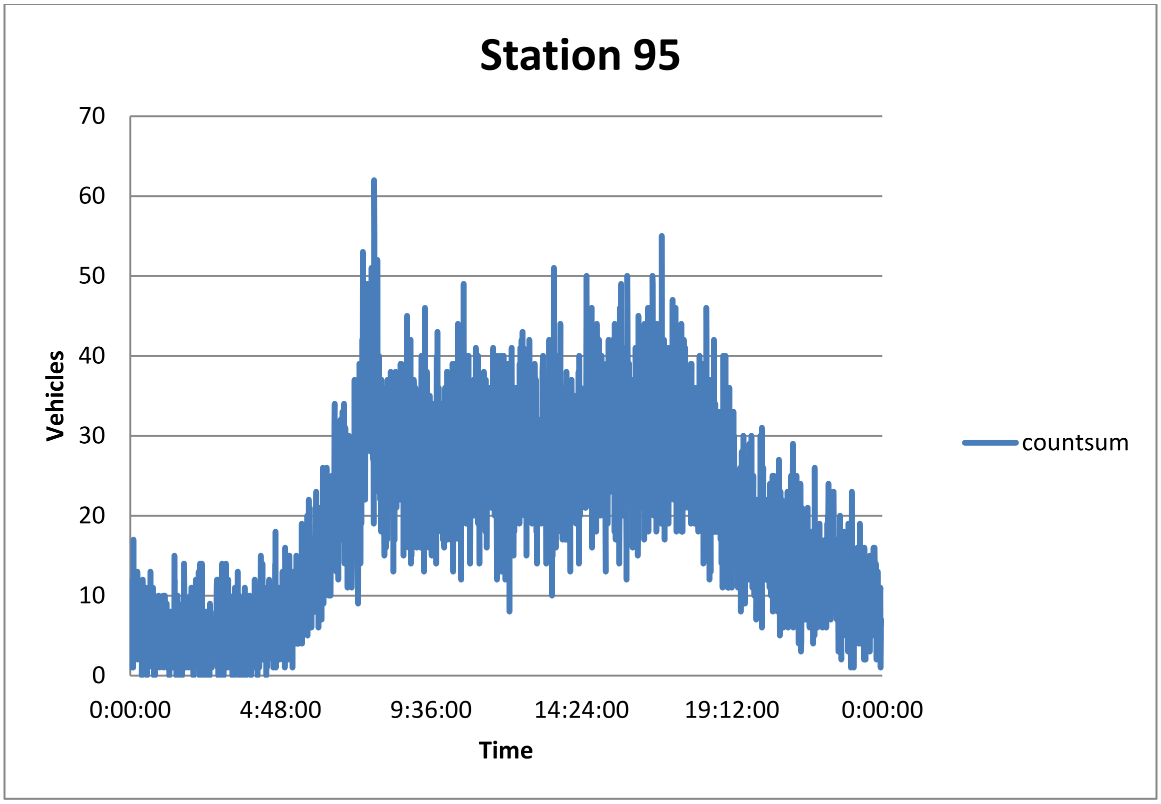


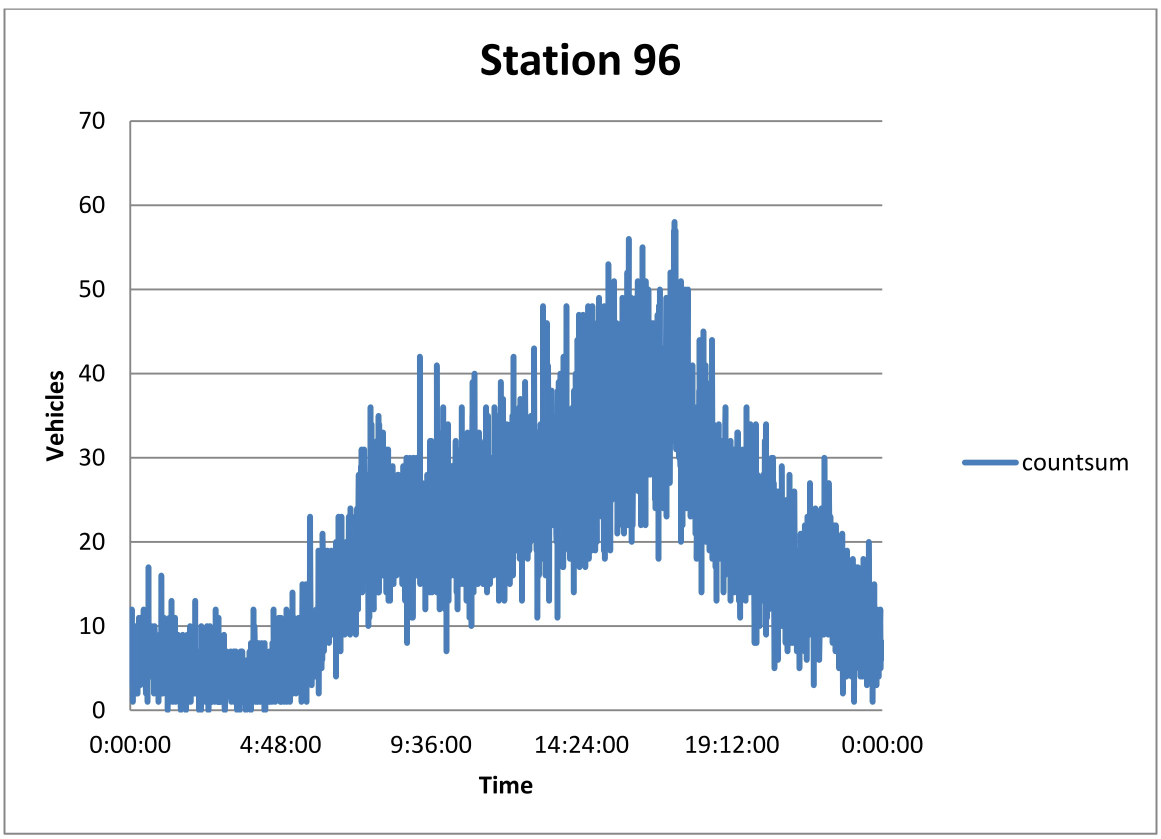

Station 176
60
50
40
30
20
10
0
Number of Cars Every 30 Seconds
0:00:00
4:48:00
9:36:00
14:24:00
19:12:00
0:00:00
Time of Day
Count

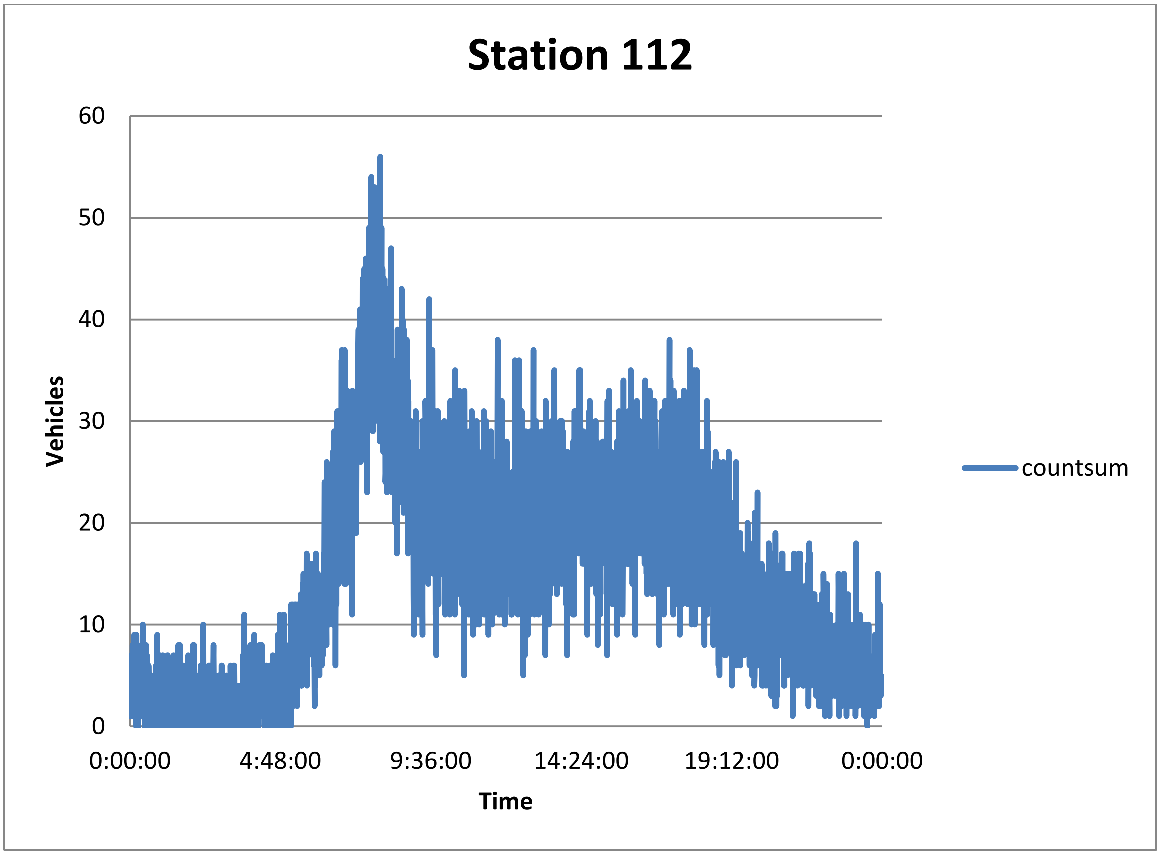

Station 177
70
60
50
40
30
20
10
0
Vehicles
0:00:00
4:48:00
9:36:00
14:24:00
19:12:00
0:00:00
Time
countsum

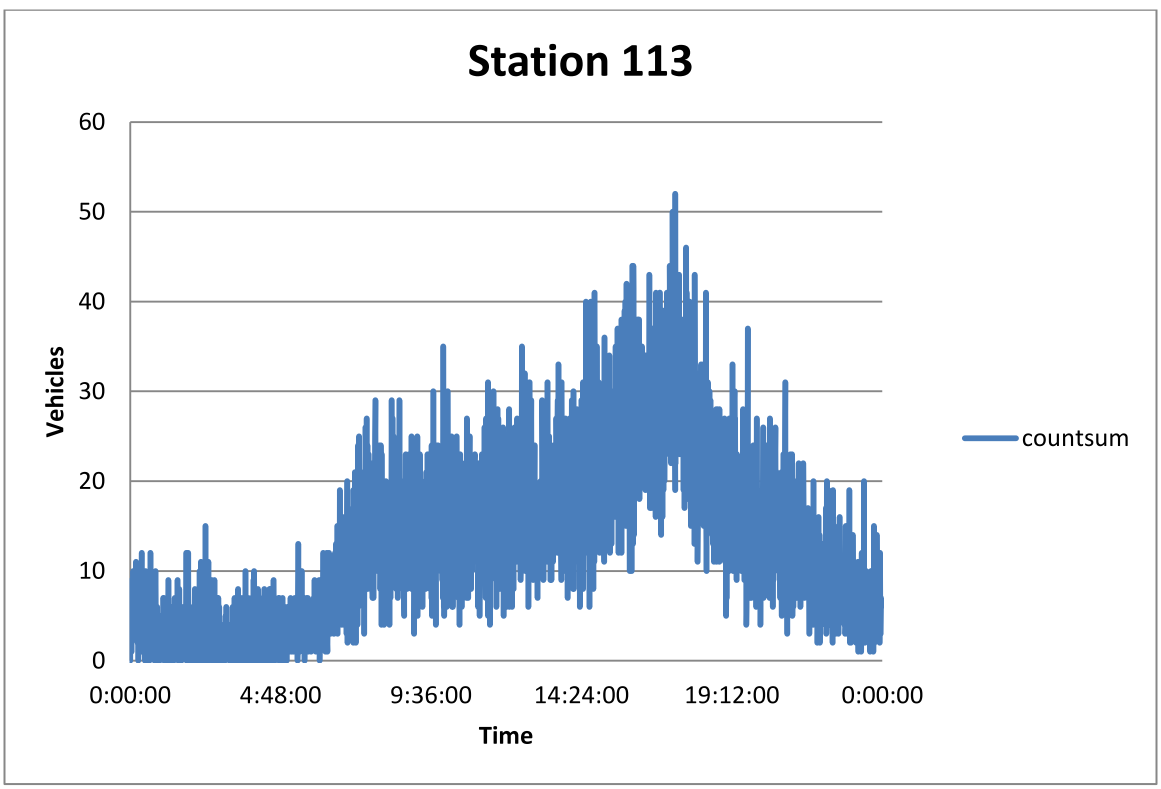

Station 184
40
35
30
25
20
15
10
5
0
Vehicles
0:00:00
4:48:00
9:36:00
14:24:00
19:12:00
0:00:00
Time
countsum

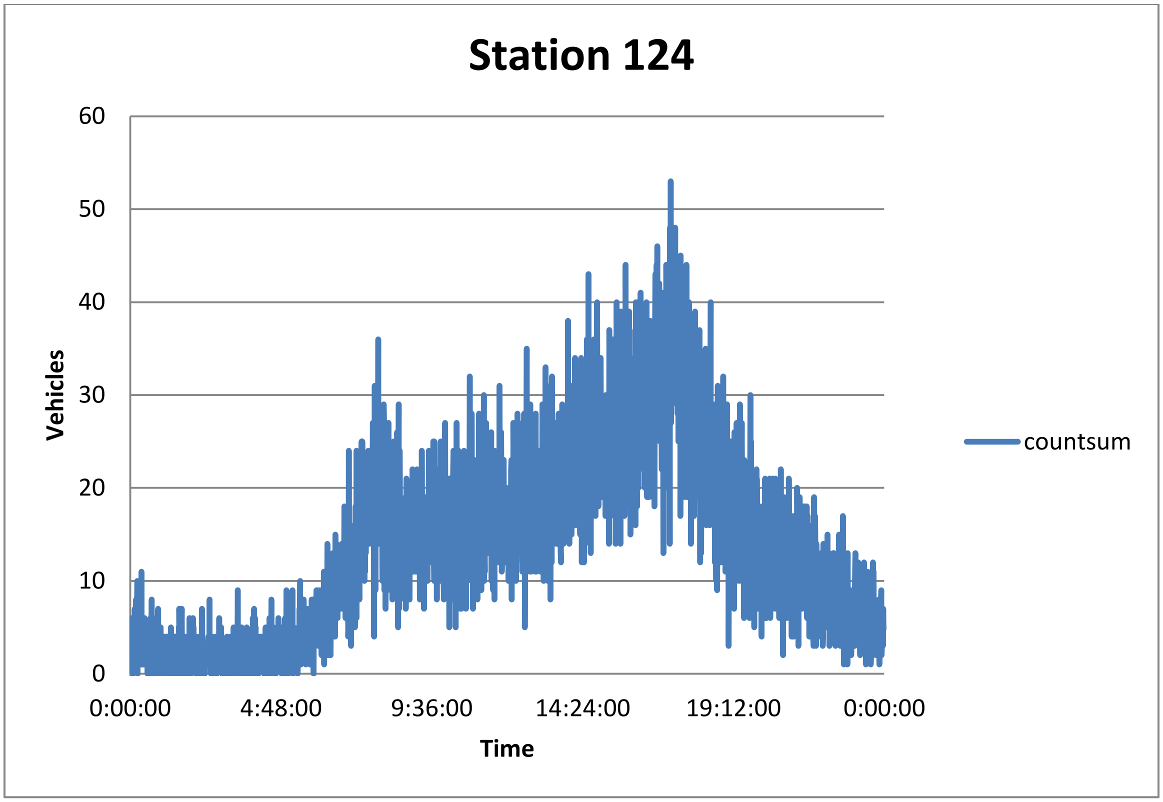

Station 183
60
50
40
30
20
10
0
Vehicles
0:00:00
4:48:00
9:36:00
14:24:00
19:12:00
0:00:00
Time
countsum

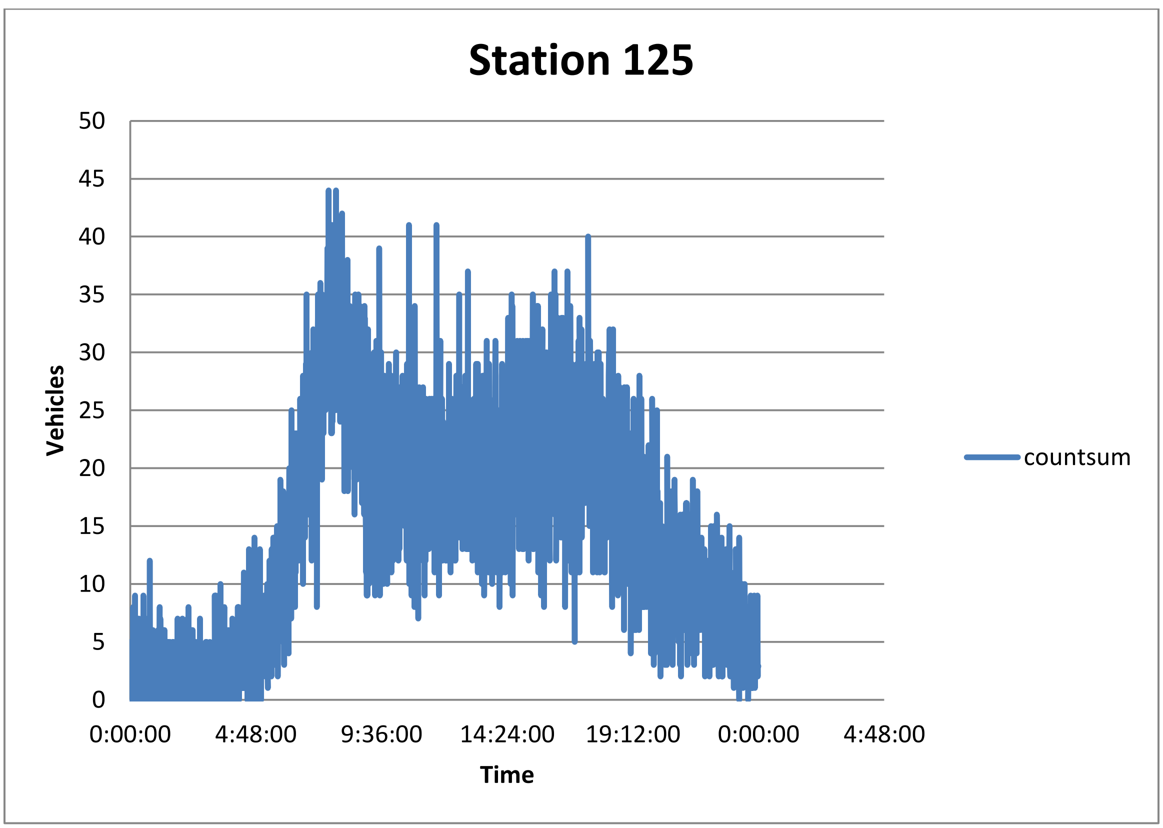

Station 95
70
60
50
40
30
20
10
0
Vehicles
0:00:00
4:48:00
9:36:00
14:24:00
19:12:00
0:00:00
Time
countsum

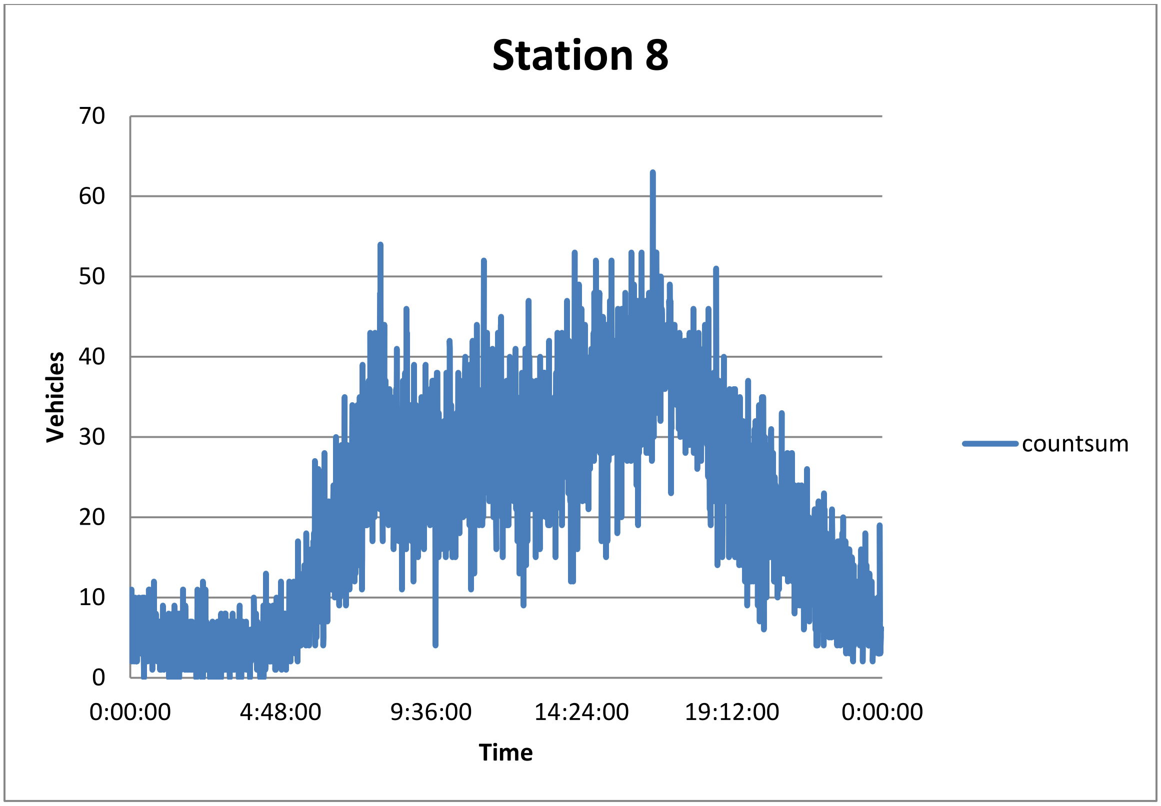

Station 96
70
60
50
40
30
20
10
0
Vehicles
0:00:00
4:48:00
9:36:00
14:24:00
19:12:00
0:00:00
Time
countsum

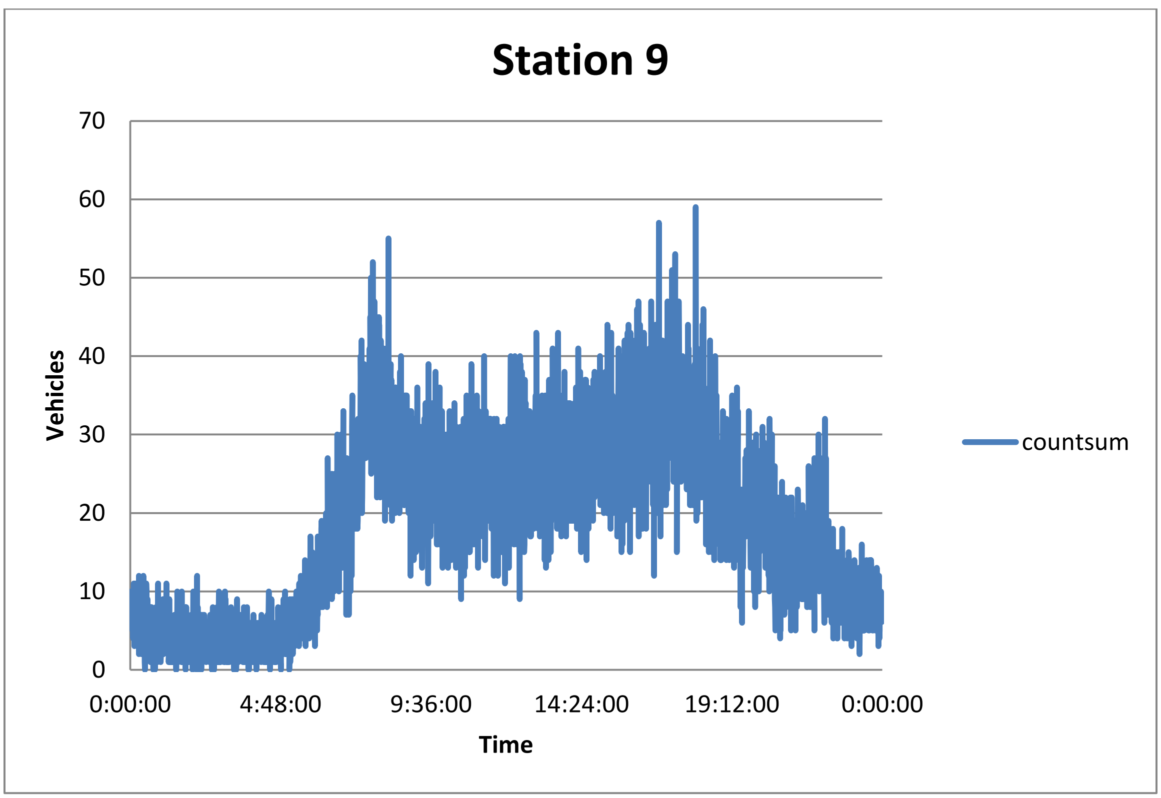

Station 112
60
50
40
30
20
10
0
Vehicles
0:00:00
4:48:00
9:36:00
14:24:00
19:12:00
0:00:00
Time
countsum


Station 113
60
50
40
30
20
10
0
Vehicles
0:00:00
4:48:00
9:36:00
14:24:00
19:12:00
0:00:00
Time
countsum


Station 124
60
50
40
30
20
10
0
Vehicles
0:00:00
4:48:00
9:36:00
14:24:00
19:12:00
0:00:00
Time
countsum


Station 125
50
45
40
35
30
25
20
15
10
5
0
Vehicles
0:00:00
4:48:00
9:36:00
14:24:00
19:12:00
0:00:00
4:48:00
Time
countsum


Station 8
70
60
50
40
30
20
10
0
Vehicles
0:00:00
4:48:00
9:36:00
14:24:00
19:12:00
0:00:00
Time
countsum


Station 9
70
60
50
40
30
20
10
0
Vehicles
0:00:00
4:48:00
9:36:00
14:24:00
19:12:00
0:00:00
Time
countsum

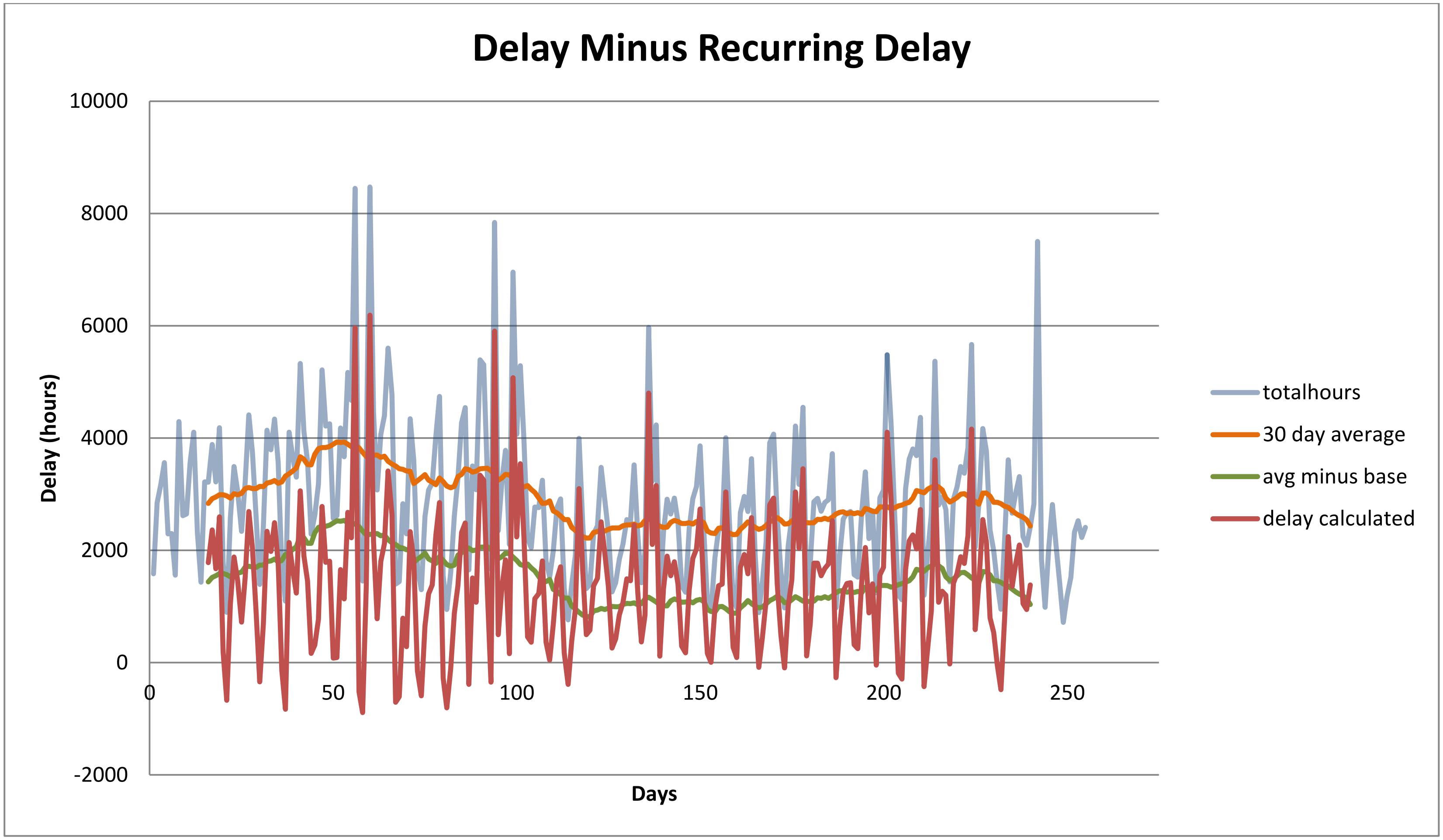
Appendix 6

Total truck and passenger car volumes for selected sections along the interstates in Knoxville. TDOT AADT is for the year 2009 and AADTT is from FHWA's FAF and is for the year 2007. AADT's given by the FAF for the year 2007 were slightly lower than the TDOT AADT.

Road	TDOT ID	AADT	AADTT	Percent Trucks
I-40/I-75 East of I-140	170	178802	7800	4.4%
I-75 North of Knoxville	257	80497	13784	17.1%
I-40 East of Knoxville	176	111421	14928	13.4%
I-640/ I-75	330	72909	11369	15.6%
I-640 East of I-75	251	68943	7040	10.2%
I-275	249	60065	3546	5.9%
I-40/I-75 West of I-140	254	121763	10937	9.0%

Appendix 7

A graph showing the delay before and after the recurring delay was subtracted out.



Appendix 8

Sensitivity analysis of the delay calculation equations.

Variables from the equations and the final values that maximize the savings in delay.

Max Savings												
TH	SI	S	lambda	delta T	delta t1	delta t2	x	y	A	AH	Savings	Ratio
6	0	6000	5999	1.00	35994	41993	35994	41993	881853000	647892000	233961000	0.3611

Sensitivity analysis performed by Microsoft Excel.

		Final	Reduced
Cell	Name	Value	Gradient
G18	delta T	1	251,957,982.03
F18	lambda	5999	231,454,231.76
D18	SI	0	(77,993.47)
C18	TH	6	35,994,000.24

VITA

Sam Moss was born in Knoxville, Tennessee and lived there for most of his life. He attended elementary through high school in Knoxville and upon graduation from high school attended the University of Tennessee. He studied Civil Engineering as an undergraduate student and completed a co-op in Atlanta, Georgia. Upon graduation he received his Engineer Intern license in the state of Tennessee and accepted a graduate research position at the University of Tennessee. Currently he is a Master's student in Civil Engineering with a concentration in transportation engineering at the University of Tennessee. He has accepted a job offer from HNTB and will begin working on the Sun Rail commuter rail system in Orlando, Florida upon graduation.